MATHEMATICAL MODELING OF ENERGY METABOLISM IN BEEF ANIMALS

By

MYRON DAVID PAINE

Bachelor of Science
South Dakota State University
Brookings, South Dakota
1956

Master of Science
University of Illinois
Urbana, Illinois
1957

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
July, 1971

MATHEMATICAL MODELING OF ENERGY METABOLISM IN BEEF ANIMALS

Thesis Approved:

Allen F. Butchbaker
Thesis Adviser

Jack E. McCroskey

Charles M. Bacon

E W Schroeder

D. Durham
Dean of the Graduate College

ACKNOWLEDGEMENTS

This graduate study was supported by the National Science Foundation Faculty Fellowship. I would like to express my appreciation to the National Science Foundation for the honor and, especially, for the opportunity of concentrating only on my studies and on the development of the mathematical model.

My sincere appreciation is extended to John Witz for his cooperation in this study. His valuable assistance as a consultant and his talents during our joint efforts together were largely responsible for the successful outcome of this project.

The assistance, consultations, guidance, support and genuine interest of my advisory committee was sincerely appreciated. The timely suggestions by Dr. Allen F. Butchbaker, Associate Professor of Agricultural Engineering, were invaluable. The technical advice from Dr. Charles Bacon, ~~Associate~~ Professor of Electrical Engineering, and Dr. Jack McCroskey, Associate Professor of Animal Science and Industries, was very beneficial. Besides the arrangements for the facilities and the funds used in this study, the sincere interest of Professor Schroeder, Head of Agricultural Engineering Department, was inspiring.

The contributions of Dr. Gordon Nelson, Head of the Agricultural Engineering Department, Ohio State University, and former chairman of my advisory committee, are gratefully acknowledged. Dr. Nelson launched this project and guided it through the formulative stages.

Looking back, I have been amazed that the variety of courses in my plan of study included the minimum required information from schools of Electrical Engineering, Mechanical Engineering, Mathematics, Animal Science, Chemistry, and Veterinary Medicine. Material learned in every course was incorporated directly into the developmental concepts. I sincerely admire the foresight and wisdom of Dr. Nelson for this selection of courses.

For assistance in preparation of figures and for typing, I extend my appreciation to Jack I. Fryrear, draftsman, and to the many typists who assisted me, especially, Ann Smith. Their specialized talents made possible the completion of this manuscript with a minimum of frustrations.

The companionship and encouragement of my wife, Birdie Lou, who endured hours of unfathomable discussion of mathematics and metabolism and who assisted diligently in the proofreading of this manuscript, has made this study rewarding.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Background

The concept of systems modeling is relatively new in engineering. The theory for systems modeling began to evolve as a specialty in the 1930's. Thirty years of work by many engineers, such as Bode, Nyquist, and Black, established mathematical relationships between the frequency response of a control system and its closed-loop transient performance in the time domain.

Developments in control theory have been particularly rapid since 1950, as high speed analog and digital computer technology was applied to the engineering problems encountered in the design of high performance aircraft and space vehicles. Within the last decade, new mathematical techniques, based upon the time domain rather than the frequency domain, have been developed. Each of these new techniques requires that the system be described in terms of so-called "state variables."

This approach consists of organizing the system equations into a vector set of first-order ordinary differential equations of the form:

$$\dot{\underline{X}}(t) = \underline{A}(t)\ \underline{X}(t) + \underline{B}(t)\ \underline{U}(t)$$

Where the $\underline{X}(t)$ are termed the state variables, and the $\underline{U}(t)$ are termed the control variables, $\underline{A}(t)$ and $\underline{B}(t)$ are matrices with time varying coefficients.

The set of equations along with a set of initial conditions at some time (t_o) completely describe the operation of the system. Thus, the state of the system at any time (t) in the future can be predicted from a set of initial conditions, determined at any time (t_o), and known control inputs U(t) from time t_o to t.

Many physical processes can be adequately modeled using state variable methods with the assumptions that the systems are continuous, lumped-parameter, and deterministic. The continuous restriction requires that the operation of the system can be modeled with differential equations; that is, the system description is continuous as a function of time. The lumped-parameter restriction requires that the system be described by ordinary differential equations instead of the partial differential equations required for a system of the distributed-parameter type. The deterministic assumption implies that there are no random variations in the system parameters. It is possible that one or more of the input variables might be described statistically.

State variable formulation of mechanical or electrical systems usually results in a set of equations that relate the transfer of energy from one portion of the system to another. The control inputs usually appear as energy additions or reductions. Thus the state variables appear to describe the energy relationships of the system.

The principles developed for modeling of conventional physical systems have also been adapted to analysis and simulation of biological systems. The first major application of systems modeling principles to biological systems occurred in the 1940's when these techniques were used to develop a model of the human respiratory system. This model of the respiratory system assisted in the design of oxygen supply for high flying aircraft. Systems modeling techniques have also been applied to develop a model of the cardiovascular system. A more recent application of biological systems modeling has been the development of simulations for eye and head movement which were used in the design of automatic gunsights for helicopters.

The application of control theory to biological systems is still mainly an art of adapting computing equipment and technology to achieve a mathematical representation of a simplified physical model of the biological system. However, the applications, to date, have proved the feasibility of using mathematical simulation to model biological systems. Also, most simulations have been developed by using lumped parameter, deterministic physical models of the biological system. Any biological system is obviously a continuous system and involves the manipulation of energy.

The term "bioenergetics" refers to the study of the processes of energy transfer in animals and the regulatory mechanisms involved in that transfer. Several disciplines, all dealing with energy transfer in animals, have developed. Biochemists are concerned with the free energy transfer which occurs in discrete chemical steps within the cells. Physiologists study the complex relationship of mechanisms and hormones that regulate the body temperature, the adult body weight, and the concentration of sugar or other metabolites in the tissue. The animal nutritionist's interest is prediction of energy demands for the animal and the ability of foods to meet these demands. Engineers have been primarily concerned with energy transfer from the animal to its environment.

An interest in bioenergetics by Brody, in Missouri, and Hammond and

Blaxter, in England, has produced considerable research by their associates on aspects of energy metabolism in animals. Some of these research projects have been extensive and thorough. In Missouri, for example, different breeds of animals were grown at different environmental temperatures, and several physiological responses were measured. There appeared to be enough validated data in the literature to serve as a basis for synthesis of a mathematical model of energy metabolism.

Development of a beef feedlot industry with one time capacities of 30,000 head or more created a need for better mathematical estimates of the effects of climate and nutrition upon beef production. The size of the new operations in the feedlot business enables them to utilize the most modern techniques for management purposes. Also the greater demands, for better mathematical estimation of the results of management decisions, encouraged the use of systems modeling techniques to develop a better mathematical model of a beef animal than existed.

A dynamic mathematical model would extend the usefulness of data from feeding trials. The results of these trials might be applied with more confidence at another location in another environment. A valid prediction method would enable agricultural engineers to design livestock systems for optimum performance considering variables of nutrition, exercise, and age of animal as well as the thermal environment. An engineer might evaluate the effects of alternate environment modification systems upon rate of gain and nutrient intake and, thus, determine a cost/benefit ratio. A valid predictor of gain for beef animals, for example, might be used in feedlots. A daily "inventory" of beef could be computed to assist with management decisions.

For these reasons, systems modeling techniques were used in this study to develop a better mathematical model of a beef animal. This report covers the development of the first dynamic mathematical model of a complete physiological system, the beef animal.

The objectives of this research were:

1. To develop conceptual models that can be used as a basis for mathematical modeling of energy metabolism of beef animals.
2. To formulate the state equations for these conceptual models.
3. To determine the validity of the conceptual models and state equations for predicting the energy metabolism of beef animals.

Procedure

The general procedure followed, in this mathematical development of a model for energy metabolism, was to: (1) assemble the pertinent data, (2) postulate a simplified physical model, (3) synthesize state equations and mathematical simulations, and (4) validate the simulation.

A library search was made to assemble pertinent data on energy metabolism in animals. Although much data was available, it needed to be compiled and recalculated to yield parameters necessary for postulation of a simplified, physical model.

Almost simultaneously with data collection and organization, the model visualization phase was conducted. During this phase a simplified physical model of the biological system was postulated so that the relationship of the variables could be determined. As necessary, recycling through the data collection and the model visualization process was done until a simplified physical model with variable relationships, established as far as possible by present data, was achieved.

The next step in the procedure was to synthesize the mathematical relationships of the physical model. The Continous System Modeling Program (CSMP) on the IBM 360/65 computer was used as a primary method of model simulation. Concurrent with the assembling of the mathematical relationships for the CSMP program, the state equations for the system were developed.

When the complete model had been assembled and verified against the data used for its development, the entire package was revised to secure better user convenience and faster computations. The final step in the procedure was to validate the model developed by comparing it to data that was not used in the formulation.

Scope of the Study

This study was limited to the energy metabolism of beef animals. It began with development of a basic conceptual model of the animal in relation to its environment. The conceptual model was used to divide the project into subunits involving related energy transfer processes.

When the major portions of the project were determined, the first stage of development of each subunit based on currently available data was completed. Subsequent revisions of subunits, involving refinement of physical and mathematical models based on data that may have to be experimentally determined, were left for future development.

Mr. John Witz, a graduate student in the school of Electrical Engineering, was also interested in applying systems modeling techniques to biological systems. He chose to model management optimization of feedlots. However, the key to his research was a good mathematical model of the beef animal. Consequently, this development became a joint effort.

Witz developed the growth section of the model and the optimization routines. Close communications were maintained so that these developments could be incorporated into the complete model along with the thermal section, digestive section, and chemical section developments. The revision of the complete model was a team effort.

The basic conceptual model was qualitatively verified before 1971. Also some development work had been done on the growth section and the thermal section. The time sequence of the developmental work is shown in Figure 1 from January 1971 through May 15, 1971, when the final model and optimization packages were put on disk. Major modeling work on the growth section and the thermal section was required until the end of February. During March the thermal and growth sections were combined, the digestive section was developed further and incorporated into the complete model. Development of the chemical section as well as development of an optimization routine to be used with CSMP were begun in March. During April the complete model was tested and an optimization was made to verify that the model could simulate the growth of an animal.

Experience with the simulation and the optimization led to the conclusion that the model, as developed, would be slow for use in practical applications and that a general performance index routine would be very useful in optimizing the model to a variety of data. Therefore, the subroutine UPDATE, created by the CSMP program, was extensively revised manually.

In the beginning, variable names for the CSMP program were created by shortening the common name of the variables or constants under con-

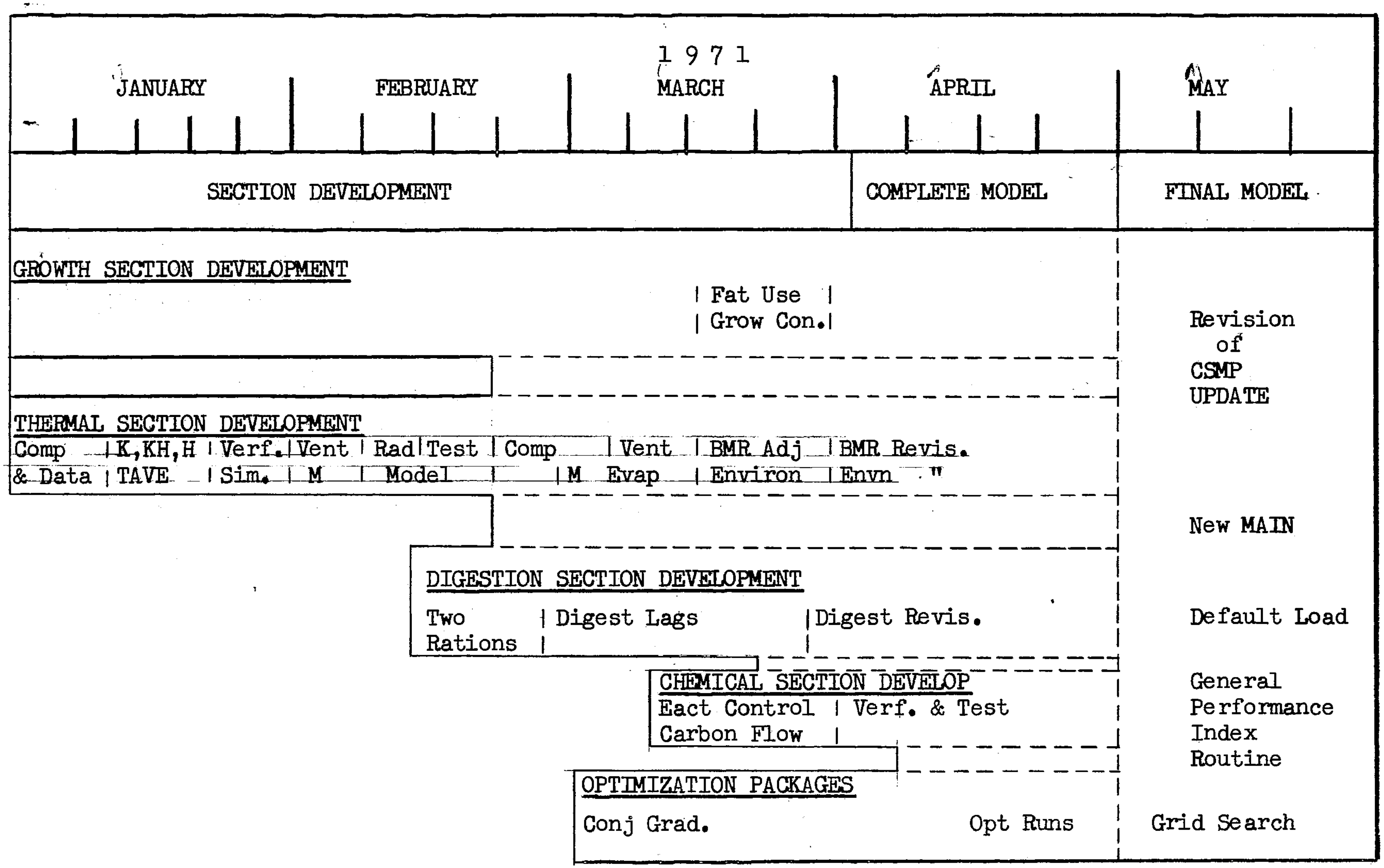


Figure 1. Time sequence chart of beef model development.

sideration. However, early in the development Witz suggested use of a systemized scheme that would designate the units of the variables. Thereafter, variable names involving energy or mass were begun with a first letter indicating the type of units associated with the variable. Standard electrical symbols were used because of their familiarity and their excellent correlation with the units involved. These symbols are listed below:

E = Energy (Kcal)
I = Rate of Flow of Mass (kg/HR)
P = Power, The rate of flow of energy (Kcal/HR)
Q = Mass (kg)
V = Energy/Mass, Energy Density (Kcal/kg)

An attempt was also made to identify constants and other variables with a consistent nomenclature. Constants were usually begun with a C. Names of animal variables, like area, were begun with A. Temperature variables were identified by a T. Multipliers, those variables computed within the CSMP program to be used similar to constants, were usually begun with a M.

Because some of the early variable names were extensively used and because programming changes often converted constants to multipliers, or vice-versa, the variable naming schemes are not completely consistent. The entire word list and the definition of variable names is contained in Appendix J. During discussion of the model sections, the CSMP names used are introduced and then occasionally used as abbreviations.

The model development required extensive revisions of schematic diagrams of subsections of the model and continued revision of the CSMP statements to improve the model performance. In some instances, model performance did not result in simulations that compared with the data.

These models were discarded. In other instances, modeling efforts were expended on subsections which were found to be either unnecessary or impractical. These were also discarded. The nature of this developmental work makes it impractical to discuss in detail the intermediate modules, their performance, or the reason for changing or discarding the modules. Therefore, diagrams and CSMP listings are presented for the modules, in CSMP form, before the final revision was made. These diagrams and listings are placed in Appendices B, F, G, and H. A complete listing of the final revised model is in Appendix I.

The mathematical calculations throughout this study were made in metric system units. However, previous research, which supplied most of the data, was reported in English units. Where English units are used in this study, they refer to the previous research. The temperatures reported in Fahrenheit degrees (F) are used only to designate the environmental conditions during the research. This labeling enables rapid orientation in the research reports. All data was converted to centigrade degrees (C) before computations were made.

The development of each subsection is discussed within their respective chapters. However, as shown by the time sequence chart in Figure 1, major developmental work on the section may have been followed sequentially by minor revisions or other additions. Although these additions or revisions are discussed within the appropriate chapter there may have been a substantial time lag between the developments. Reference to the time sequence chart will assist in understanding of the developmental sequence. The abbreviated symbols in the time sequence chart should become clearer as the following text is studied.

The review of literature in Chapter II covers the information utilized in this development. The description of the basic conceptual model in Chapter III introduces the overall relationships of the model and is useful for orientating the following chapters within the total concept. The growth section of the model is discussed in Chapter IV. Chapters V, VI and VII describe the development of the thermal, digestive and chemical sections respectively. Verification and revision of the complete model, and validation against other data is discussed in Chapter IX. Discussion, conclusions, and use of the model in a management example are included in Chapter X.

CHAPTER II

REVIEW OF LITERATURE

Systems Modeling

Systems modeling is an area of engineering that began with attempts to apply the concepts of electronic amplifiers to servomechanisms. The technology has developed rapidly and has been applied to diverse applications including simulation of existing physical, biological and socio-economic systems. From a small handful of papers and books on the subject in the 1940's, the literature production rate has increased to a floodtide of texts and papers. For example, Brockett, 1970, has an incomplete list of 93 references. Of these references, less than 10 were written before 1960. Several of these early references refer to classical mathematical developments in the nineteenth century and the traditional basic papers of control system theory in the early 1930's.

Many of these publications are engineering texts which rely heavily on mathematical developments and which cannot be properly detailed in a review of literature. However, the techniques and concepts of control system theory form the basis of this study on simulation of energy metabolism in beef animals. Therefore, a brief review of systems modeling development, its associated computer technology, and state space concepts will be made.

Control of Servomechanimsms

The original work in systems theory was an attempt to design and assemble control circuits for servomechanisms. Thus, the early texts in this field were mainly concerned with mathematical methods for synthesizing control systems. Because these control systems involved electrical components, the primary factors for consideration were amplitude attenuation and phase shift of the steady-state sinusoidal electrical signals. For each component, a transfer function, the ratio of output to input as a function of frequency can be determined. Then the response of the system can be estimated by correct mathematical combinations of the transfer functions. The mathematics associated with the study of the steady state sinusoidal electrical signals are called the frequency domain transformations.

Mechanical and hydraulic systems can also be described by equations similar to those used for electrical systems, allowing the use of the same analytical methods. Electromechanical transducers also contribute their particular transfer functions to the total system.

The Laplace transform is a useful tool in the study of systems. It enables differential equations to be transformed into relatively simple algebraic equations which can be analyzed and manipulated into a desired form. Essentially the Laplace transform eliminates time, t, as the independent variable in differential equations. The substitution of the Laplace operator for time and the use of transformation rules allows initial conditions to be included as the Laplace transform is written and allows for transformation back to the time domain once a solution is obtained. The Laplace transformation enables the study of transients as well as steady-state sinusoidal signals. Texts covering these topics include D'azzo and Houpis, 1966, Leondes, 1961, Murphy, 1966, Nixon, 1953, and Schwarz, 1965.

System synthesis involves determining the transfer functions in individual components and relating these transfer functions by block diagrams to achieve the total system transfer function. Analytical techniques for evaluation of the system include methods such as root locus plots and frequency response plots. Graphical interpretation of the system's parameters by these plots can be used to determine the stability of the system and to improve its performance.

Digital and Analog Computers

Concurrent with the development in system theory, computing technology has advanced. Analytical methods are difficult to apply to systems having many interconnections. Therefore, the use of digital and analog computers is often employed.

The electronic analog computer is well suited to the solution of simultaneous differential equations. The analog computer can also operate in real time and can couple physical hardware with mathematical representations of other systems. For these reasons analog computers are often used in system analysis. Techniques for analog implementation are discussed by Korn and Korn, 1964, Leondes, 1961, McCollum, 1968, and Nixon, 1953.

Analog computers have a major disadvantage in that their average accuracy is only within ±2 to 3 percent. The solution to a complex system involving major components having greatly different time constants may require more accuracy than an analog computer can achieve. For that reason, analog and digital computers may be coupled together in a hybrid configuration to determine or to control parameters for complex systems. The analog section solves that portion of the system requiring rapid time solutions. The digital section handles the portion of the system that requires decision making and control of the system parameters. These applications are covered in Korn and Korn, 1964, and McCollum, 1968.

State Space Analysis

When large, complex systems are encountered, the techniques of Laplace transformation are often not capable of solving the problems. Also, techniques for connecting the integrators of an analog computer result in writing equations for each integrating unit in the system. Thus a system of first order differential equations is usually developed in the process of preparing a mathematical model.

The equations for analog implementation can be represented in terms of the vector matrix differential equation:

$$\dot{\underline{X}}(t) = \underline{A}(t)\ \underline{X}(t) + \underline{B}(t)\ \underline{U}(t)$$

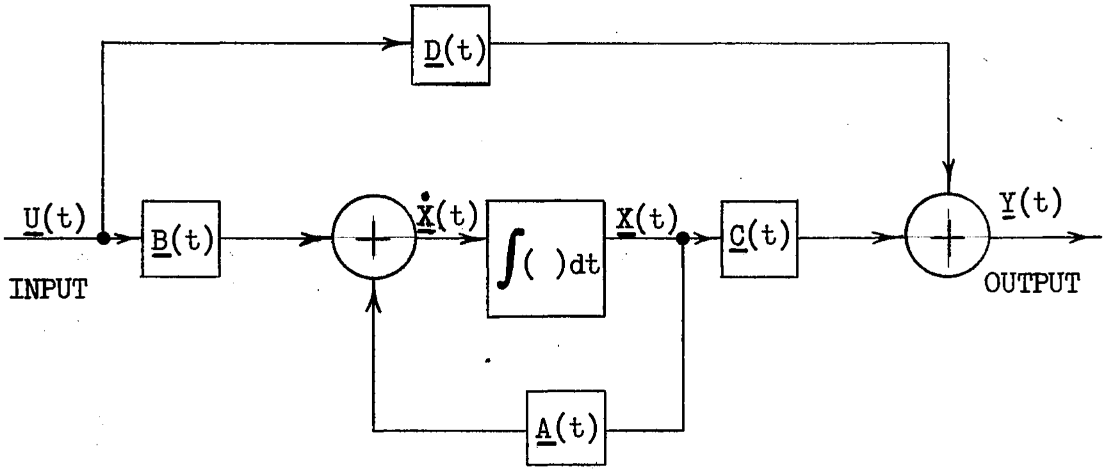
where $\underline{X}(t)$ is a n vector, $\underline{U}(t)$ is a m vector, $\underline{A}(t)$ is a n by n matrix, and $\underline{B}(t)$ is a n by m matrix. This formulation is called the state space equation. A more general version of this equation can be written for non-linear systems. This state equation, along with an output equation

$$\underline{Y}(t) = \underline{C}(t)\ \underline{X}(t) + \underline{D}(t)\ \underline{U}(t)$$

where $\underline{C}(t)$ is a n by n matrix and $\underline{D}(t)$ is a n by m matrix, completely describes the response of this system. Thus, knowing the initial conditions and the input functions, the performance of the system at any time, t, in the future can be predicted by integration of the state equations. The output equation is a linear combination of the state and the input variables.

A representation of the relationships of the state and output equations is given in Figure 2. The primary objective is to define mathematically the first derivative of the state variables. Although the equations and representation are for linear systems, the same concepts are applicable to non-linear systems. Non-linear systems usually require computer solution.

The mathematical expertise to analytically solve state equations by employing matrix algebra has also developed rapidly. Vector matrix notation greatly simplifies description of the systems equations. The notational simplicity of vector matrix operation is essential for theoretical analysis of complex systems.



$\underline{X} = \underline{A}(t)\ \underline{X}(t) + \underline{B}(t)\ \underline{U}(t)$ STATE EQUATIONS

$\underline{Y}(t) = \underline{C}(t)\ \underline{X}(t) + \underline{D}(t)\ \underline{U}(t)$ OUTPUT EQUATIONS

Figure 2. Typical Linear System

One of the advantages of the analog computer is that it can provide rapid continuous integration of differential equations. Integration routines can also be performed by digital computers. Programming to obtain the solution of a system on the analog computer is simpler than programming a digital computer. Therefore, digital computer programs were written to simulate analog computers. One of the major advantages of these programs is that the scaling procedure, required for using analog computers, can be eliminated. This elimination of scaling and use of analog techniques on a digital computer provides a method of rapidly transferring a physical or socio-economic system into a mathematical model. Thus, use of Pactol, Dynamo, or the continuous system modeling program, CSMP, of the International Business Machine Corp., 1968, becomes a very useful tool in the mathematical modeling of physical, biological or socio-economic systems. CSMP became the major tool of this study.

A mathematical model of the system is prepared by assembling mathematical models of the system components and a model of their interconnection pattern. When properly modeled, the behavior of any component in the system is independent of how the component is interconnected with other components. Thus, individual components can be studied and modified without changing the behavior of the remaining components. Also components of the system can be replaced by another system of components that provide a better mathematical model of the component action. In this manner, the researcher can go as far as desired in breaking the system down in search of basic building blocks. In the physical sciences, the basic building blocks are already defined and have rigid mathematical relationships. In the biological or the socio-economic fields, the systems components are not yet well defined.

Computer methods and mathematical techniques are becoming available to enable engineers to select the best numerical parameters to secure a given performance from a system. It is possible to use similar mathematical routines to establish the numerical parameters involved in a biological or socio-economical system. This topic is covered in Citron, 1969, Eveleigh, 1967, Ogata, 1967, and Sebesta, 1969. Techniques discussed by these authors were used in this study to solve for parameter values that could not be determined directly from data.

As a conclusion to this section, a portion of a flow diagram of system theory from Koenig, 1967, is included in Figure 3. This flow diagram illustrates the steps required for synthesis of a mathematical simulation of any system. The main steps included in this diagram are; (1) system identification, (2) formulation of the component and interconnection models, (3) creation of the state models, (4) machine simulation, (5) response characteristics of the simulation, (6) calculation of performance index and (7) parameter optimization to minimize the performance index. The procedures to accomplish these steps in the flow diagram are discussed in detail by Koenig, 1967. Essentially, these steps for system modeling were followed during the development of the beef model. Thus, Figure 3 is also a schematic of the procedures used in this study.

Modeling of Biological Systems

One of the first attempts to design a model showing energy utilization by animals was done by Kleiber in 1936. His model

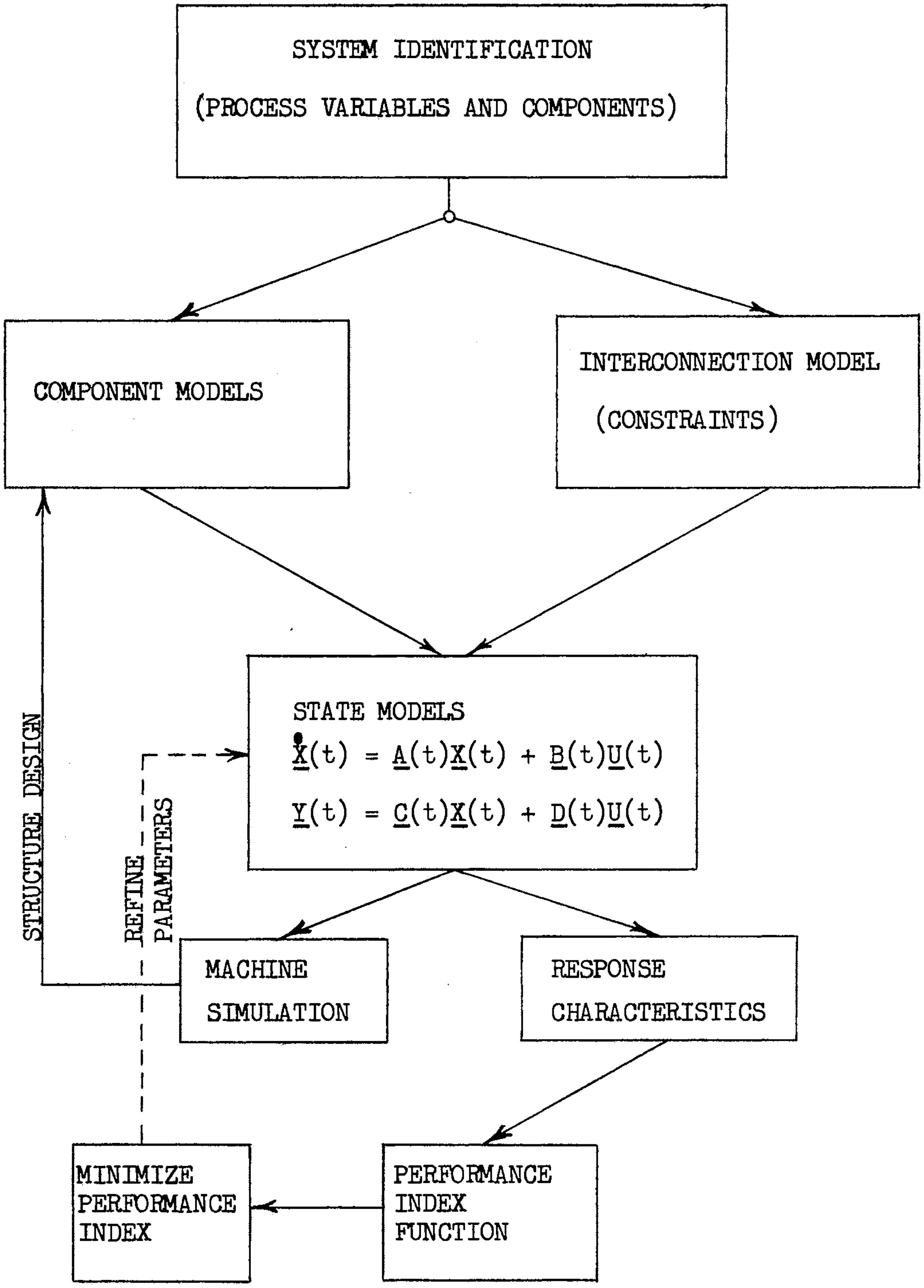


Figure 3. Flow Diagram of System Theory

reproduced in Figure 4 was based upon a hydraulic scheme. Basically, the model consisted of several interconnected reservoirs. Intake and utilization of food energy was represented by a liquid flowing through a system of tubes and reservoirs. The conceptual model featured mechanical control mechanisms that responded to the nutritional demands of the animal. This conceptual model formed the basis for this study.

Biological Systems Analysis

In the past decade there have been several applications of system theory to biological systems which are summarized by Link and Splinter, 1968. This review will cover only those mathematical models related to animal simulation, primarily energy metabolism. However, several mathematical models have also been developed for simulation of plant growth, grain drying, grain unloading and harvesting.

There is a scarcity of books applying systems analysis techniques to biological systems. Three major texts have been written by Grodins, 1963, Milhorn, 1966, and Milsum, 1966, blending system theory and its application to biological or physiological systems. These texts were utilized as handbooks during the model development.

Grodins, 1963, extensively reviewed basic system theory and analytical techniques for the frequency domain. A section of the book presents detailed mathematical models for analog simulation of the respiratory chemostat and the cardiovascular regulator. A combination of these two models is proposed but not developed completely. The techniques employed to develop these mathematical models are examples of the application of engineering skills in biological sciences.

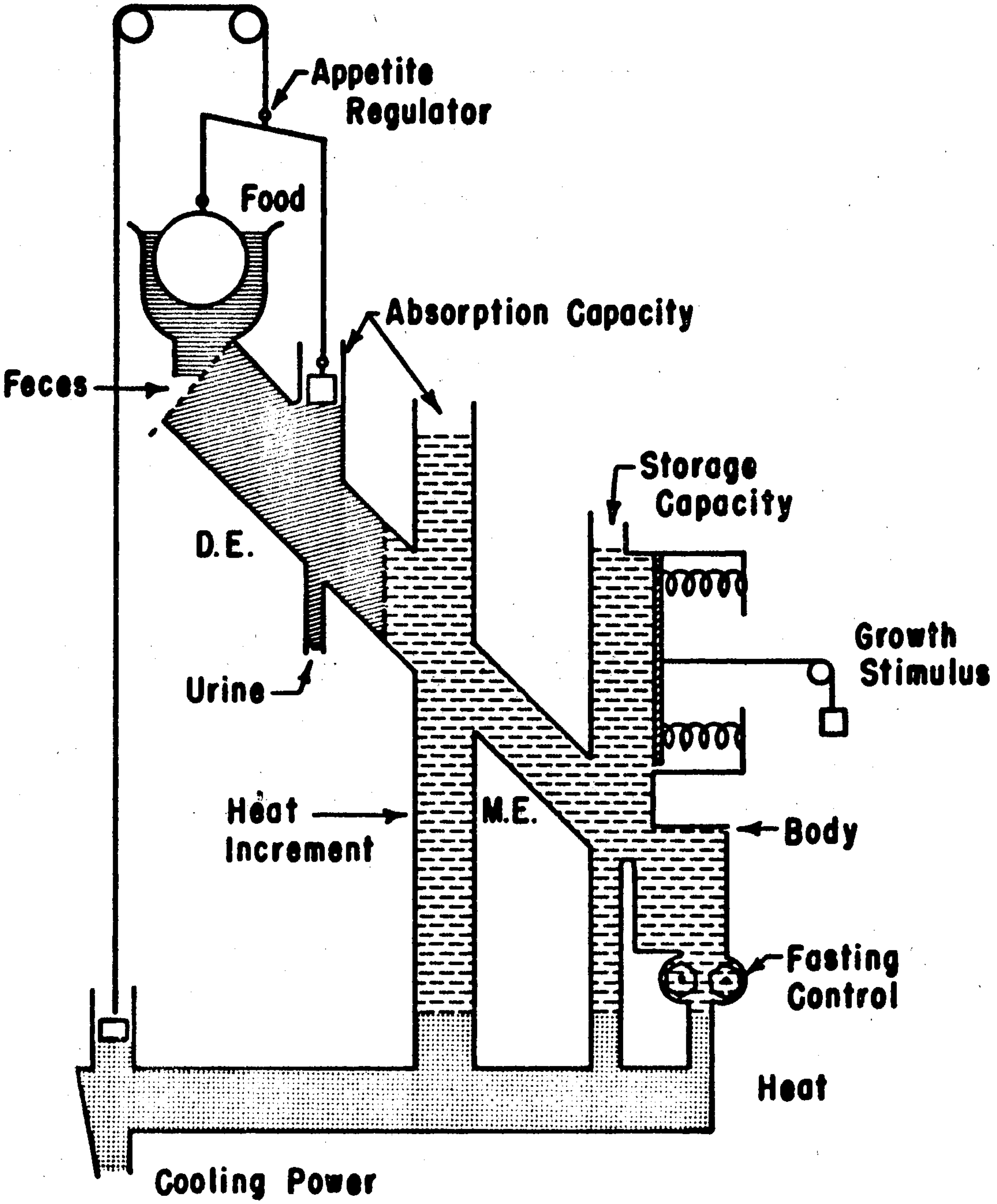


Figure 4. Schematic diagram of Kleiber's hydraulic model to represent energy metabolism in beef animals.

Milhorn, 1966, following the same general pattern as Grodins includes chapters on obtaining the differential equations for several physiological systems. The major emphasis is on the respiratory and the cardiovascular systems. Simulations of the human eye tracking an object and of the stretch reflexes in the human muscle are presented in detail.

Milsum, 1966, illustrates basic control theory principles with biological examples. The biological systems covered in detail include oculomotor systems and skeletal muscle servomechanisms. Statistical signals in biological systems are also presented plus brief treatments of other control concepts, such as adaptive control.

Applications of System Theory in Biology

More recent literature describing application of advanced systems techniques to biological applications has appeared as published proceedings of symposiums and conferences. The most consistent example of systems applications to biological systems is the Proceedings of the Conference on Hormonal Control Systems edited by Stear and Kadish, 1969. This conference covered specifically the four hormonal systems: (1) adrenal cortical function, (2) glucose and metabolic fuel homeostasis, (3) thyroid function, and (4) gonadal function. For each of the hormonal systems, the known physiology and the modeling aspects were presented. As compiled, this proceedings provides an excellent summary of the physiology and the present state of the mathematical modeling for the four hormonal systems.

At the conference on Hormonal Control Systems, Charette, Kadish and Sridhar, 1969, reviewed the previous modeling attempts to simulate glucose homeostasis. They conclude that a meaningful system model for metabolism will involve nonlinear mathematics. This conclusion implies that the analytical difficulties will necessitate the use of computational facilities for simulation purposes.

In the same conference a paper on the thyroid and pituitary system modeling by Distefano and Stear, is an example of the progress that can be made in the understanding of physiological responses by using systems modeling techniques. Their diagram of thyroid and pituitary interrelationships is shown in Figure 5. This diagram and the associated paper were key elements in the development of a basal metabolic rate controller for the beef model in this study.

The Proceedings of the Third Systems Symposium at the Case Institute of Technology edited by Mesarovich, 1968, covers a broad aspect of system theory application to biology. The first part of the symposium was devoted to the basic conceptual question of relations between system theory and biology. The second portion of the symposium contains critical reviews of some of the principle areas in biology in which methods and techniques of system theory have been applied. The third portion of the symposium consists of contributions considering specific biological problems, from the biochemical level up to the central nervous system. The proceedings, as published, contain contributions from the first and third parts of the symposium. In general, these papers cover either the physiological and biological systems or theoretical developments in systems mathematics which might be applied to biological systems. A specific example of system theory applications to a biological system was presented by Yates, et al, 1968, on the adrenocortical function.

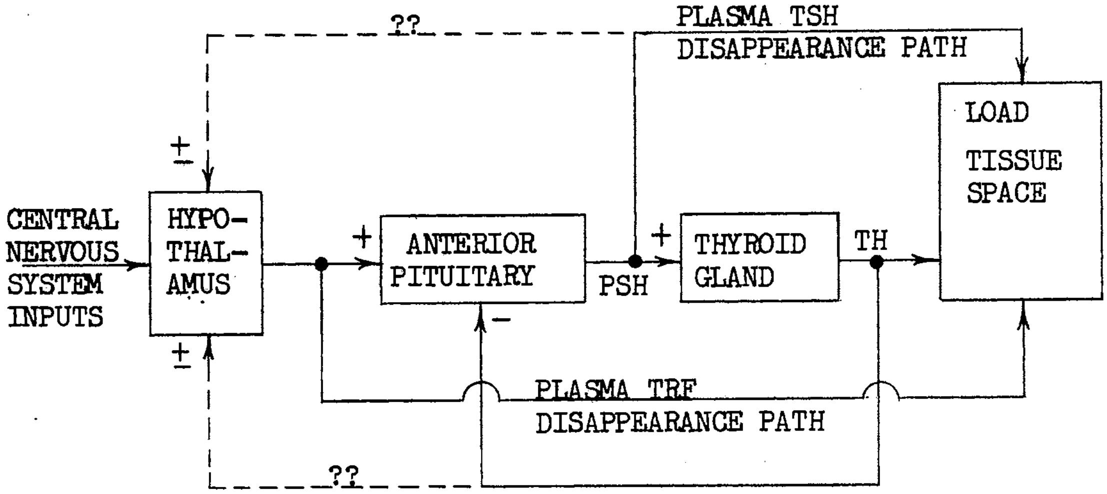


Figure 5. Schematic of pituitary-thyroid interaction to control thyroxine concentrations in the blood.

Another proceedings, edited by Yamamoto and Brobeck, 1965, considers application of systems theory to physiological systems. This book is a collection of seminar papers dealing with temperature regulation, carbon dioxide balance, control of breathing, control of water exchange, the cardiovascular system, and gastric secretion in the intestines, as well as other topics. The discussions vary from technical mathematical modeling of the set point temperature to general description of various physiological systems.

Another book by Reine, 1968, refers to simple feedback systems and analog circuits in the discussion of enzymatic control for rates of chemical reaction. However, his book, on the organism as an adaptive control system, is primarily devoted to chemical systems. He describes the processes of biochemical coding for genetic inheritance, including sequencing of DNA and RNA and proteins.

Kalmus, 1966, assembled articles on regulation and control in living systems from specialist authors in each field. The result includes a basic introduction to systems theory and a series of papers related to physiological and biological phenomena discussed in relation to possible control principles. The section on regulation and control in the endocrine system is very detailed and complete.

The major developments of system theory application to biological systems are covered in the textbooks and the proceedings of seminars. However, other applications, published as technical papers, illustrate the diversity and usefulness of mathematical modeling.

Simulations of Biological Systems

One of the best developments for analog simulation of temperature regulation in man was done by Crosbie, Hardy, and Fessenden, 1961. A mathematical model, using the electronic analog, was constructed to simulate the physiological responses to heat and cold in a nude man. Heat losses by radiation, convection and evaporation were taken into account by the mathematical model. The simulation predicted steady state situations of rectal temperature, skin temperature, metabolic rate, vasomotor state, and evaporative heat loss under both resting condition and exercise. The simulation of dynamic responses to sudden shift in environmental temperature, air velocity, relative humidity and metabolic rate was also possible. This mathematical model was developed assuming a physical model of a slab of the proper dimensions to represent heat flow from the interior of the body to the skin surface. The model and the developmental techniques formed the basis for the thermal section of the beef model in this study.

A computer simulation of non-linear blood flow was prepared by Crosby and Klukis, 1968. An application of digital computers for dynamic simulation was done by Johnson and Scott, 1969. They developed a mathematical model which reproduced steady state conditions and transient frequency response for thermal receptors. A mathematical model for digital simulation of the basic relationships for thermal homeostasis in a chicken was developed by Bouchillon, Reece and Deaton, 1969. A mathematical model of heat transfer from a pig was developed by Beckett and Vidrine, 1969. Their mathematical model is a set of empirical equations based upon results obtained in other studies. A system diagram was used by Mason, Shanklin and Stewart, 1965, to represent the arrangement of the elements to explain the physiological behavior of the temperature regulating system of an animal.

Growth

The prediction of the weight of an animal as a function of time has been considered by many authorities for several decades. Medawar, 1945, summarized the five most popular formulas for growth versus time. These formulas, were developed from attempts to fit empirical data. The formulas involved coefficients, also determined empirically, for the species of animals under study.

Brody, 1945, presented a series of curves showing the weight of animals plotted as a function of time. These logarithmic curves for various animals are remarkably similar. In fact, by altering the time scale, Brody superimposed the curves on one graph.

Weight as a Function of Energy

The level of energy input affects the shape of the logarithmic curve for body weight plotted against time. This phenomenon was also illustrated by Brody, 1945, who presented a series of curves showing the difference in growth rate as affected by energy expended in labor. Those animals having less energy available for growth, developed slower and did not reach the same final weight at maturity.

Although the body weight is affected by available energy, it appears that the growth of the skeletal dimensions is not greatly altered. Brody illustrated this effect by graphing human height versus time where one of the subjects studied had to work harder than the other. The same effect was also shown by an illustration of skeleton height of steers fed at two different levels of energy.

Based upon a study involving twin heifers reared under nutritional control, Taylor and Young, 1966, concluded that animals receiving similar amounts of feed had similar growth rates and feed efficiencies. Also, animals growing at the same rate appeared to consume the same amount of feed with the same efficiencies. Their experimental results were used for a validity check of the completed beef model in this study and their curves showing feed intake and body weight as a function of time are presented in Chapter VIII.

Differential Growth, Body Composition

The growth rate of various parts of an animal body differ. Hammond, 1961, basing his comments on research done on lambs and pigs, presented curves and illustrations to support his concept of differential rate of growth. The priority of some components of the body, especially the brain and the skeleton, over fat and muscle growth was discussed. Hammond concluded that bone structure of animals was determined largely by the inherited traits. However, differences in the shape of bones were also produced by changes in the level of nutrition. If the level of nutrition was low, the bone might grow in length but the thickness growth would be retarded.

Hammond, 1961, also reported that different levels of nutrition at different periods in the animal's life can change the composition of the body. Underfed animals had a higher proportion of bone to meat and fat. However, animals fed a high level followed by a low level of energy also had high proportions of bone to meat and fat. This body composition occurred because a large frame developed which then continued to mature at the expense of meat and fat. Animals fed on a low level of energy followed by a higher energy level had a higher proportion of meat to bone.

The work by P'lasson and Verges, 1952, 1955, contained several growth curves of lambs as a function of input energy. However, some of the lambs were dissected at birth, nine weeks, and forty-one weeks. The skeleton muscle, and fat fractions were determined as representative of the composition of the living lambs. These fractions are shown in Figure 6.

McMeekan, 1940, 1941, reported on growth and development in pigs. He concluded that skeleton, muscle and fat developed in that order. The three tissues had differential rates of growth. Also, for any one type of tissue, regions of the body showed well defined differential

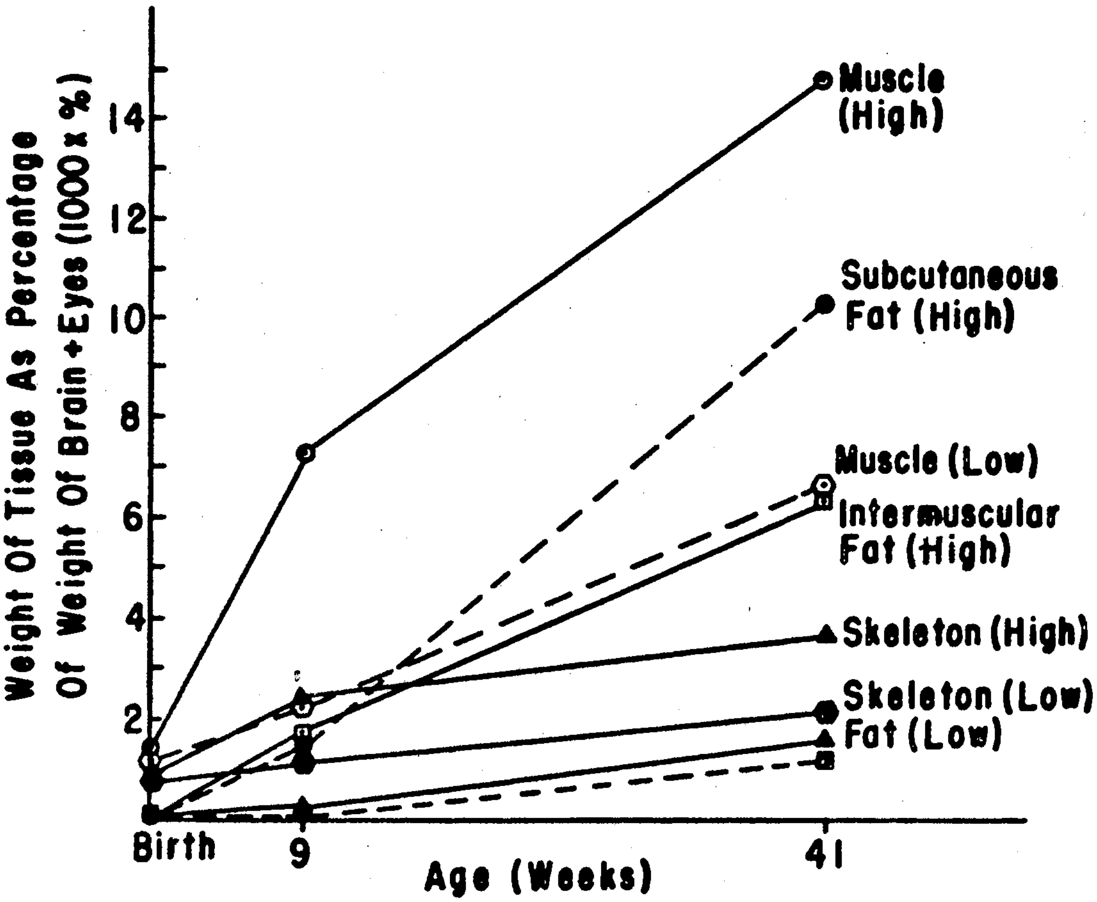


Figure 6. Differential growth rates of body tissue for lambs fed two levels of energy.

growth relationships. The body organs showed marked heterogenic growth. The parts essential to life appeared well developed at birth and made a smaller amount of growth in postnatal life than the body as a whole. Those organs whose function was primarily concerned with the storage of nutrient reserve did not develop until the later stages of growth.

Animals that are fed in a manner to produce normal continuous growth have a predictable composition that appears to be closely related to weight. Reid, et al, 1968, have presented data to support this relationship between body composition and weight. They also showed that the age of the animal had very little influence as a predictor of body composition. Extreme stress, when the animals were forced into a fasting condition, was the only factor that appeared to vary the composition of animals at the same weight.

The effectiveness of body weight as a predictor of body composition is revealed by efforts of Frahm, Walters and O'Dell, 1970, to develop other methods of live evaluation, such as K^{40} count. These methods require high precision to exceed the 5-8 percent standard error of estimate of formulas based on weight alone. The characteristics of differential growth, energy dependence and predictable composition, at least for skeleton and meat tissue, were incorporated in the growth section of the beef model which was developed by Witz.

Weight Versus Environment

Johnson and Ragsdale, 1959, reported upon a 12-month investigation conducted to determine the influence of constant environmental temperatures of 50 F and 80 F on physical growth responses of Holstein, Brown Swiss, and Jersey calves. The growth of the Holstein and Jersey calves was depressed at the high 80 F environmental temperature. The Brown Swiss animals did as well at 80 F as at 50 F.

The effect of temperature and age combination upon weight gains was observed in the various breeds. The Holsteins and Jerseys raised at 50 F had higher rates of gain than the animals raised at 80 F until approximately 8 months of age. The 80 F animals were making greater gains toward the end of the experiment. Relative breed differences were also demonstrated by these young growing dairy calves.

A similar study was done with Brahman, Shorthorn and Santa Gertrudis calves. Ragsdale, Cheng, and Johnson, 1957, concluded that the Shorthorn calves had reduced growth rate of 80 F because their high heat generation rate created heat stress conditions. The Brahman calves with a lower heat generation rate did not have a significantly different growth rate.

These reports indicate that different breeds have different abilities to adjust to high thermal environments. Apparently the basal metabolic rate of each breed is a hereditary factor that must be considered in relation to the environment. Reduced food intake, resulting in depressed growth, appears to be a symptom of animals with high heat generation rates attempting to reduce thermal overload. A provision to specify the basic metabolic rate as a hereditary factor was included in the beef model.

Growth Control

Parpart, 1949, and Needham, 1966, discussed the chemistry and physiology of growth processes in animals. Needham stated that the endocrine system acts as a master control of the growth process throughout life. He further postulated that a particular hormonal ratio, related to body size, must exist. Growth can be interrupted but will resume at the same rate as before.

According to Goss, 1967, many kinds of growth are stimulated by the physiological demand for increased functional activity. Therefore, normal growth in animals may be controlled by the necessities of physiological activity. Expanding organs need to change only fast enough to keep pace with the increasing size of the body.

But, functional activity per se does not denote growth. Excessive availability of substrate appears to promote the activation of more enzymes to aid in the conversion of that substrate to its end product. Apparently, the demand for functional activity and growth is an unbalance of substrate to the final end product.

However, on an enzyme level, the substrate demand for functional activity, noted by Goss, has developed into a realization that feedback control regulation also takes place in enzymatic reactions. Lehninger, 1970, reports that study of feedback processes is a new and expanding area in biochemistry.

For the normal growing animal, Taylor and Young, 1964, concluded that appetite and growth rates were genetically controlled. This conclusion was a result of an experiment involving twin calves. Genetically heavier animals consumed more feed and also appeared to be more efficient. Taylor and Young developed a linear nomograph model for maintenance and growth efficiencies to explain the variations between animals.

The various aspects of growth control, reported above, were incorporated into the beef model. Hormonal control of the basal metabolic rate was modeled as a function related to body size. Growth was modeled as a response to a substrate concentration. Heredity factors for growth and basal metabolic rate were included in the model.

Physical Factors of Heat Transfer

Surface Area of Bovine

Early investigators felt that the area of the skin was a primary factor in the heat balance of animals. Therefore extensive studies have been done in order to develop mathematical equations of the area of the skin of farm animals.

An equation representing the surface area of 341 beef cows, computed by Matthews and Brody, 1928 is:

$$A = 0.12W^{0.60}$$

where A is the area in square meters and W is the weight in kilograms.

The surface area of the skin of 96 dairy cows was measured by Elting and Brody, 1926. They plotted the surface area as a function of weight on logarithmic paper and illustrated the excellent fit of the data to a curve defined by the equation:

$$A = 0.15\ W^{0.56}$$

Where A is the area in square meters and W is the weight in kilograms.

Elting and Brody reported that the average error was estimated to be 1.9 percent. Brody, 1945, felt that the equation, based on weight alone, was sufficient to describe the surface area of dairy cattle.

The surface area of beef animals was investigated by Hogan and Skouby, 1923. They developed a prediction equation based upon length and weight of the animal. Their equation is:

$$S = 217W^{0.4}L^{0.6}$$

where S is the surface area in square centimeters, W is the weight of the animal in kilograms, and L is the length in centimeters of the animal measured from the shoulder blade to the rump. To be able to use this formula, reference to a table showing the length as a function of the weight is usually necessary.

Johnson, et al., 1961, reported surface area and body weight relationships for dairy calves raised at different environmental temperatures. Using the standard equation $A = aW^b$, they found that the coefficient (a) varied from 0.21 to 0.34 and the exponent (b) varied from 0.39 to 0.48. Those animals raised under heat stress at the higher environmental temperature may have developed their skin area at a slightly faster rate. Prediction of surface area was important in the development of the thermal section of the model. All of these equations were examined closely to determine their usefulness.

The heat generated by digestion of food and body metabolism is lost to the environment at a rate which allows the animal to maintain a relatively constant body temperature. This heat transfer to the environment must be accomplished by conduction, convection, radiation or evaporation. Therefore, the physical principles describing these methods of heat transfer will also apply to an animal. However, as discussed below, the use of heat transfer theory and classical equations may be more difficult than with physical systems because of the complex problem in determining the proper coefficient values.

Only those aspects of heat transfer theory and research that were employed in the beef model development are discussed. The one exception is the research done by Weirsma, 1966, who developed equations relating the surface heat transfer coefficient to air flow. This information is included because dynamic implementation of the outdoor environment requires Weirsma's relationships. However, the modeling done in this study used data from indoor environments and did not require Weirsma's results.

Conduction

Heat is transferred between an animal and objects that it contacts. The fundamental equation for steady-state heat conduction through a material is given by:

$$q = -kA \frac{dT}{dx}$$

where A is the cross sectional area, $\frac{dT}{dx}$ is the temperature gradient k is the thermal conductivity, and q is the heat energy transferred per unit time.

In practice an animal loses a minimum amount of heat by conduction when it is standing. When the animal is lying down, the ground beneath the animal warms up so that the conductive heat loss is diminished. Also, Spillman and Hinkle, 1969, report that the animal may adjust the conductive heat flow to the ground by physiological means. Blaxter, 1962, estimates that the amount of heat transferred to the environment by conduction is considered to be insignificant compared to the heat transfer by convection, radiation and evaporation. However, heat transfer within the body or through hair coats becomes a factor in dynamic simulations. In this case, the animal is often represented as a cylinder.

If heat is being conducted through a cylinder of length L with an internal radius of r_1 and an external radius of r_2 the equation for steady-state heat transfer becomes:

$$q = -k\,(2\pi rL)\,\frac{dT}{dr}$$

which can be integrated to give:

$$q = 2\pi kL\,(T_1 - T_2)/\ln\,(r_2/r_1)$$

For animals the value of k may vary or is difficult to determine.

Physical hair characteristics which might affect the transfer of heat through animal hair coats were determined by Berry and Shanklin, 1961, and correlated with measured insulation values. They concluded that hair orientation, as estimated by depth over length ratio, had more influence than other measured variables on hair coat conductivity. Increasing depth over length ratio for hair of a constant length resulted in a decline in the amount of heat transferred through the entire depth of the hair coat. Also, increasing numbers of hair per unit area increased the total heat transferred, indicating that the heat transfer along the hairs was a major portion of the total.

The measurement of heat flow by Berry and Shanklin, 1961, was done with Gier and Dunkle heat flow meters that made direct heat flow measurements. Heat flow measurements were made at two different environmental temperatures, 65 and 90 F. The average total insulation values obtained at an air temperature of 65 F was 0.6155 F-hr-Ft^2/BTU, compared to an average of 0.2682 F-hr-Ft^2/BTU obtained at the 90 F temperature. Therefore, the authors concluded that environmental temperatures influenced either the measuring technique or some physical characteristic of the hair coat which was not measured. This evidence supports the conclusion, reached during the thermal section development, that beef animals can control hair resistance to heat transfer.

Convection

By convection an animal can lose heat to air circulating around it. The amount of convective heat transfer is described by the following relationship:

$$q_{cv} = \underline{h}\, A\, (T_1 - T_2)$$

where q_{cv} is the convective exchange of the heat, A is the animal surface area, $(T_1 - T_2)$ is the temperature difference between air and animal surface, and $\underline{h}$ is the average convection coefficient which will vary as a function of many physical factors including air velocity.

The convection coefficient can be defined from experimental data by use of dimensionless parameters which include:

Nusselt Number	$\underline{Nu} = \underline{h}\ d/Kf$
Reynolds Number	$Re = \rho VL/\mu$
Prandtl Number	$Pr = \mu Cp/Kf$
Grashof Number	$Gr = L^3 \rho Bg \Delta t/\mu^2$

where d is the diameter of the cylinder, K_f is fluid conductivity, ρ is the fluid density, V is the air (linear) velocity, μ is the fluid viscosity, C_p is the fluid specific heat, B is the coefficient of thermal expansion, g is gravity acceleration, Δ t is the temperature difference, and the other symbols are as defined above.

For the usual environmental temperature range the Prandlt Number can be considered a constant and the Nusselt Number becomes a function of the Reynolds and Grashof Number.

$$\underline{Nu} = f(Re,\ Gr)$$

An extensive investigation of convection coefficients for sensible heat transfer was done by Wiersma, 1966. He concluded that the effect of the buoyancy forces in air was slight and that reasonably accurate predictions of convection heat transfer could be made regardless of the direction of the air flow by using the equation:

$$\overline{Nu} = 0.65\, Re^{0.53} \qquad 10,000 < Re < 160,000$$

to determine the Nusselt Number, from which the convection coefficient can be calculated.

Wiersma also concluded that, as long as more than two or three inches of clearance between animals existed, the location of other cattle had no effect upon convection cooling. Animal orientation to the direction of horizontal air flow also did not affect convective cooling. The results of this study were also compared by Wiersma to information from other researchers. The conclusion was that the convective heat transfer coefficient for cattle ranged from 0.66 to 3.12 $BTU/Hr\text{-}Ft^2 - F$, depending upon the temperature and the velocity of the air. Weirsma's equation would be applicable for modeling wind effects on the surface heat transfer coefficient, but it was not implemented in this study.

For free air convection, Wiersma predicted that the convective heat transfer could be determined by the equation:

$$\overline{Nu} = 6.85\, Gr^{0.137}$$

where $\overline{Nu}$ is the Nusselt Number as before and Gr is the Grashof Number. The results predicted by this equation were not compatible with other research data. As the environmental temperature increased, this equation predicted decreasing $\overline{Nu}$ numbers, but the $\overline{Nu}$ numbers calculated from data on live animals increased.

Radiation

All surfaces radiate, absorb, or reflect energy in amounts that depend upon the temperature and the character of the surface. Any two surfaces are continually exchanging heat at a rate that is defined by the physical equation:

$$q_r = \frac{\sigma\,(T_1^4 - T_2^4)}{\left(\frac{1-E_1}{E_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-E_2}{E_2\,A_2}\right)}$$

where q_r is the radiation heat exchange, A_1 is the area of one surface, A_2 is the area of the other surface, σ is the Stefan-Boltzmann constant, F_{12} is the factor that allows for the relationship of one surface to another, T_1 and T_2 are the absolute temperatures of the two surfaces, and E_1 and E_2 are the radiation characteristics of the two surfaces.

Heat transfer by radiation between the animal and its environment is complex. Radiation received by the animal can be considered to have two main components, the near infrared component and the far infrared component. The average wave length of the maximal radiation is the basis for this classification. An approximation to the wave length of the maximal radiation can be made by the Weins displacement law, which states that the product of the absolute temperature of the radiating object and the wave length of the maximal radiation is 0.288 centimeter-°K. The sun with a temperature of about 6,000 °K would have a wave length of maximal radiation of approximately 0.4 microns. An object at a temperature of 0 °C. would radiate energy at a wave length of about 10 microns.

A black body that absorbs all of the radiation which strikes it has an emissivity of 1. Actual materials have variable emissivity values which vary with the particular wave lengths of the radiation being absorbed. The hair coat of animals, irrespective of color, has an emissivity of about 0.95 to 1.0 for all far infrared radiation but for near infrared radiation the emissivity varies as a function of the hair color.

For beef animals, the radiation heat load, or relief, can be calculated by procedures which estimate the contributions of radiation from hot unshaded ground, the horizon, the cool sky, the hot sun and, if used, the hot shade overhead and the cool shaded ground.

On warm summer days animals receive less radiation from the sky, except for the direct sun, than from the surrounding ground. In a study on solar radiation, Ittner, Bond and Kelly, 1958, concluded that an area in the north sky at approximately 60 degrees above the horizon could be used as a heat sink in warm weather. A difference of about 28 degrees was available as a cooling sink between air at temperature of 100 F and sky temperature.

Evaporation

The rate of mass transfer between an animal's surface and the surrounding air by evaporation can be described by the following equation:

$$\dot{M}_a = hm\ (W_s - W_e)$$

where $\dot{M}_a$ is the mass transfer per unit time per unit area, hm is the mass transfer coefficient, W_s is the humidity ratio at the skin, W_e is humidity ratio at some reference point in the air.

The above equation appears to be similar to the heat transfer equation for convective cooling. It has been determined that there is a correlation for convective mass transfer and convective heat transfer. Both of these phenomenon appear to be related to the skin friction coefficient. If heat and mass transfer occur simultaneously, the mass transfer coefficient can be estimated from the following formula;

$$h/h_m = \rho C_p(Le)^{2/3}$$

where h is the heat transfer coefficient for convection, h_m is the mass transfer coefficient for convection, ρ is the density, C_p is the specific heat at constant pressure, and Le is the Lewis number which is defined as the thermal diffussivity divided by the molecular diffussivity. Experiments have confirmed that equations to predict the mass transfer coefficient of cylinders in transverse air flow are remarkably similar to equations developed to predict the heat transfer coefficient. Jakob and Hawkins, 1961, suggest that, where experimental data is not available, mass transfer coefficients can be estimated from heat transfer data.

Under many circumstances the humidity ratio at the animal's skin surface is apparently less than would be predicted by using the saturation density at the temperature of the skin surface. The probable cause is the lack of saturation wetting by sweat glands of the animal. The sweat glands of cattle do not provide a visibly wetted skin surface under normal conditions.

Physiology and Environment

Major research to determine the relationship between the environment and the physiological responses of cattle has been done at the Agricultural Experiment Station at the University of Missouri. These researchers conducted two major projects to determine the physiological effects of cattle growing in two thermal environments. One of these projects involved three beef breeds and the other project used three dairy breeds.

During the first research project Shorthorn, Brahman, and Santa Gertrudis calves were grown from the approximate age of 1 to 3 months until all animals were approximately 16 months of age. Experimental groups of three animals of each breed were raised at constant 50 and 80 F temperatures. A control group was raised in variable outdoor temperatures. Measurements made on these animals included determination of energy metabolism, rectal temperatures, respiratory rates, pulse rates, pulmonary ventilation, oxygen consumption, carbon dioxide and methane production, stable heat and moisture dissipation, dimensional and weight changes, feed and water consumption, vaporization rates, blood volume and total extracellular body water, thyroid counts, surface temperature and area, hair growth and density, and ovarian and physical activity.

Bulletins published on this research included Ragsdale, Cheng, and Johnson, 1957, Yeck, 1957, Johnson, Ragsdale, Cheng, 1957, 1958, Johnson, Ragsdale, Yeck, 1958, Blincoe, 1956, 1958, Dale, Ragsdale, Cheng, 1959, Kibler, 1957, Kibler and Yeck, 1959, and Stewart and Shanklin, 1958.

A similar research project was conducted using Brown Swiss, Holstein, and Jersey dairy calves. These calves were again divided into experimental groups at 50 and 80 F environmental temperatures. The calves were grown until they were approximately 12 months old. As before, the results were reported in a series of bulletins by Berry and Shanklin, 1961, Johnson and Ragsdale, 1959, 1960, Kamal, Johnson and Ragsdale, 1959, Kibler, 1960, and Johnson, 1961.

Because these two experiments were similar and so comprehensive the results will be discussed together. The data from these experiments was used extensively in model development in this study.

Results of the Missouri Experiment

At 50 F, breed differences in body or rectal temperatures were minor. The body temperatures of the animals at 80 F were slightly higher than the body temperatures at 50 F. Only the Shorthorn breed experienced difficult adjustment to the 80 F temperature. The rectal temperatures of these Shorthorn calves averaged about 2 F higher throughout the experiment than for other breeds. In all breeds the rectal temperature appeared to decrease with advancing age.

Changes in respiratory rate occurred as a function of the temperature but not as a function of age. All of the animals in the higher temperature environment had higher respiration rates. The Shorthorn had, by far, the highest respiration rate; nearly twice as much as the other animals at the same temperature.

The pulse rate showed definite age effects, reaching a peak at 4 to 6 months of age followed by a decreasing rate. Although there appeared to be a difference between breeds, the effect of the temperature was minor except for the beef animals raised at 80 F.

The pulmonary ventilation rates for all animals raised in the 80 F environmental temperature were higher than the ventilation rates of the animals raised at 50 F. The higher ventilation rate was required even for those animals having slightly less body weight than similar breeds grown at 50 F.

The energy metabolism as a function of body weight was fitted to the equation $Y = aX^b$. To secure a good fit to the data, two sets of coefficients and exponents had to be determined for each curve.

The heat production per unit area was not constant but rose to maximum level at about 6 months of age, at body weights from 350 to 450 pounds. With the beef breeds the heat production per unit area then decreased. With the dairy breeds the heat production per unit area continued to increase very slightly. The rate of heat production per unit weight for all animals, except the Shorthorns at 80 F, appeared to be unaffected by the environmental temperature. The heat production rate per unit weight increased until approximately 4 months of age and then declined rapidly until an age of about 10 months was reached. Then the heat production rate per unit weight continued with a slight decline.

The 80 F environmental temperature was severe enough to depress the growth rate and also the skeletal growth of the Shorthorns to a certain extent. The growth rate of the Holstein cattle was also affected by the higher temperature. The other breeds of animals did not appear to be greatly affected by the different environmental temperatures.

High environmental temperatures caused a gradual decrease in the thyroid secretory activities of all calves. Significant negative correlations were obtained between high environmental temperatures and the thyroid release rate. In the constant temperature environment the thyroid secretory activities of Shorthorn heifers was decreased by about 45 percent at the 80 F temperature.

The constant 80 F environmental temperature significantly depressed the energy consumption of the Shorthorn and Santa Gertrudis calves. Relation of feed and water consumption to body weight during growth at both 50 F and 80 F showed distinct "breaks" in the logarithmic regression line at approximately 200 pounds for all animals except for the Shorthorn raised at 80 F.

Skin vaporization accounted for 55 to 72 percent of the total vaporization in calves raised at 50 F, and for 64 to 82 percent of the total vaporization in the calves raised at 80 F. High vaporization rates in the Shorthorn animals raised at 80 F were associated with their body temperatures and were not evidence of superior evaporative capacity. Skin vaporization from small areas was found to be greatest on the upper body surface and lowest on the under body surface.

Increasing body weight in a 80 F environment was associated with decreasing skin temperature and increasing hair temperature, except for the Shorthorn main body hair. However, the Shorthorn's hair had been clipped for heat relief. In the 50 F environment the skin and hair temperatures both decreased with increasing weight. When the animals were subject to changing environmental temperatures from 65 F to 110 F, it was found that the previous constant temperature environment had little or no effect on the skin or hair temperature.

Effects of Environmental Temperature

There is other evidence to indicate that environmental temperatures affect physiological systems of animals. Ragsdale, et al, 1950, 1951, found that energy intake, measured as TDN per 100 pounds of body weight, for dairy cattle remained essentially constant until critical high ambient temperatures between 75 and 85 F were reached. Increasing environmental temperature above these temperatures rapidly depressed the feed consumption so that it virtually stopped when a temperature of 105 degrees F was reached. The same effect was also demonstrated with growing dairy heifers. However, feed consumptions for the heifers did not decline as rapidly until after 95 degrees temperature was reached. The growing heifers appeared to be able to use more water for heat relief than the milking cows.

Johnson, et al, 1962, 1963, determined that temperature and humidity had significant effects upon total digestible nutrient (TDN) consumption in cattle. Combinations of high temperatures and high humidity produced significant decreases in TDN consumption. The rectal temperature of the animals was recorded and correlated to the decrease in TDN consumption. There appeared to be approximately a 3 pound/day decrease in TDN consumption for each degree rise in rectal temperature. Water and TDN consumption were also related to a temperature-humidity index, but the relation appeared to be highly non-linear.

A study of rectal, rumen, and environmental temperatures by Brody, Dale and Stewart indicated that they tend to vary together in diurnal rhythms. The temperature of the rumen appears to average about 4 F above the rectal temperature. Following a 24 hour fast the rumen temperatures decreased approximately 3 F.

Above the critical level of 70 to 80 F the rectal temperature and respiration rates increased in dairy cattle while the heat production and pulse rate decreased. Kibler and Brody, 1950, 1954, reported Brahman cows also had a critical temperature level which appeared to be about 95 F. The authors suggested that the lower heat production rate of Brahman cows may be a factor in their greater tolerance to heat. Decreasing temperatures from 50 to 9 F did not affect the rectal temperature, decreased the respiration rate very slightly in Holstein and Jersey cattle, and increased the heat production rate more in Brahman than in Jersey and Holstein cows. All cattle experienced an increase in heat production rate as the temperature dropped.

At Missouri, the relationship of radiant energy to physiology has also been studied. Kibler and Brody, 1954, demonstrated that increased radiation increased rectal temperature and respiration rate of Holsteins and Jerseys. The heat production rate was also depressed by 12 percent in the Jerseys and 26 percent in the Holsteins. Graphical analysis of the data indicated that radiation rates of 500 Kcal/m2/hour at 70 F air temperature provided a heat stress equivalent to a 10 F rise in air temperature without radiation. Studies by Bedwell and Shanklin, 1962, and Shanklin and Stewart, 1958, were reported on cooling dairy animals by use of refrigerated air panels. The results of these studies indicated that refrigerated panels were effective in reducing respiration rates, skin temperature, hair temperature, water consumption, and ambient air temperature above the animal's back. However, refrigerated panels were not effective in reducing rectal temperatures although they did reduce the slope of the rectal temperature versus time transient as the cattle were adjusting to the panels.

The effects of wind on physiology of dairy animals was also reported by Kibler and Brody, 1954. At 17 F, increased wind velocity resulted in increased heat production in Holstein, Jersey and Brown Swiss cows without disturbing the animal's rectal temperature. Under similar conditions Brahman cows increased their heat production by 6 percent but were unable to prevent a fall in rectal temperature of about 1 F. At temperatures of 50 and 65 F the increased wind velocity had little effect on total heat dissipation. In general non-evaporative heat losses were greater but they were balanced by smaller heat losses by vaporization from the respiratory tract and the skin. At higher temperatures the effect of increased wind velocity was to reduce the rectal temperatures more toward normal. Lowering of rectal temperatures from 1 1/2 to 2 degrees F was reported for the animals at 95 F and wind velocities of 8 to 9 miles per hour.

The benefits of increased air movement on beef cattle in high environment temperatures was also demonstrated by Ittner, Bond, and Kelly, 1958. With average air velocities as low as 3 1/2 miles per hour they measured reductions in rectal temperature of over 1 F between calves in the pen with mechanical ventilation and those calves in a similar check pen. Animals in the mechanically ventilated pen gained significantly more weight than those animals in the check pen.

High environmental temperatures also cause changes in the hormonal systems within cattle. Blincoe and Brody, 1955, reported that increasing ambient temperature to 95 F has decreased thyroid activities 30 to 65 percent in four breeds of cattle. Ambient temperatures below the comfort zone resulted in increased thyroid activity in some animals but not in others. Dale, Burge and Brody, 1956, reported that cattle have had increased serum and blood volumes as their environmental temperatures increased.

A well documented study by Pedersen, 1968, resulted in an unprecedented conclusion that the only regulation necessary for the maintenance of the total heat balance is a thermostatic control within the body. This controller can regulate the heat transporting blood stream from the interior to the skin as well as the secretion of sweat from the glands. This information supports some of the concepts utilized during development of the thermal section of the beef model.

Food Digestibility

One of the primary factors of energy metabolism in animals is the digestibility of the food ingested. It is necessary to know what percentage of the energy is actually absorbed by the animal and what factors affect the absorption of this energy. Also, especially for ruminant animals, it appears that the products absorbed by the body will vary depending upon the type of food ingested.

Reid and Tyrrell, 1968, in a survey of experimental literature on the level of intake to energetic efficiency, concluded that the effect of level of intake on digestibility by sheep and cattle depends upon the chemical and physical nature of the diet. The digestibility of long or chopped forages is not affected as the level of intake increases. However, the digestibility of finely ground forages and of grain decreases as the level of input increases. There is some association with the decrease in digestibility to the increase in the rate of passage of the material through the animal's gut. The ingesta passes through the gastrointestinal tract of ruminants more readily when the diet is of small particle size than when it is coarser. Also the rate of passage of small particles is more rapid at high intake levels than at low intake levels.

The effect of level of intake and digestibility of various diets by cattle is shown in Figure 7. The curves demonstrate that a decrease in relative digestible energy (DE) appears to be a function of the percentage of concentrate in the diet and the level of intake. The few data points available indicate a linear response to both the level of intake and the percentage of grain. From research data collected by Wagner, 1967, the decrease in digestibility appears to be a linear function of the grain concentration.

Another source of energy loss, besides the feces, that must be considered for ruminant animals is the energy loss by methane production and by heat. The heat loss by methane production in a ruminant when expressed as a percentage of the heat of combustion of the food is remarkably uniform. However, energy loss as methane gas, expressed as a fraction of the energy of the food, does increase slightly with the apparent digestibility of the diet and does decrease with the level of food intake. The usual percentage of energy loss as methane production varies from 6 to 8 percent depending upon the apparent digestibility and the level of intake.

There are several factors which might logically be considered important in digestibility but which apparently have no or very little effect. These factors include the genetic makeup of the animal, the age of the animal, and the frequency of feeding. Among ruminant animals at the same level of input there is less than a 2 percent variation in digestibility within the species. Except for the very early

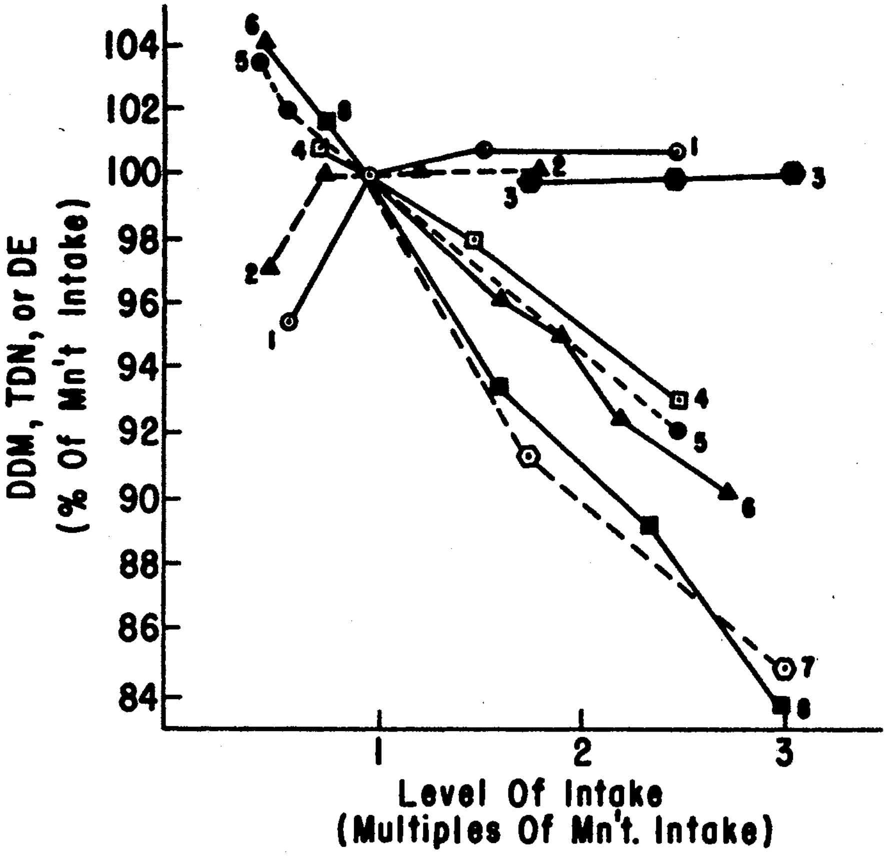


Figure 7. Effect of level of nutrient intake on digestibility.

Lines represent following diets:

1. Alfalfa hay (Hale et al., Jour. Dairy Sci., 23:953. 1940).
2. Mixed clover-timothy hay (Watson et al., Sci. agr., 15:476, 1935).
3. Alfalfa-bromegrass-Ladino mixture; fresh, green harvested forage fed to dry cows (Reid et al., unpublished data. 1956.)
4. Diet of concentrates (33%) and hay and corn silage (67%) (Eckles, Mo. Agr. Exp. Sta. Res. Bull. 4, 1911).
5. Corn silage (Watson et al., Sci. Agr., 19:622. 1939).
6. Diet of concentrates (80%) and mixed hay (20%) (Reid et al., unpublished data, 1953.).
7. Diet of concentrates (60%) and hay (40%) (Trowbridge et al., Mo. Agr. Exp. Sta. Res. Bull. 18. 1915).
8. Diet of corn grain (75%) and hay (25%) (Mumford et al., Ill. Agr. Exp. Sta. Bull. 172. 1914.).

days of life, there appears to be no appreciable change in the digestibility of food by an animal as it grows older. Also with ruminant animals there appears to be no effect on the digestibility of food fed several times a day compared to feedings once or twice a day.

Feeds Description

According to Maynard and Loosli, 1969, most of the usual animal feeds have about the same gross energy per unit weight on a dry basis. However, the digestibility of feeds can vary greatly, depending upon whether it is forage or concentrate. Animal nutritionists have conducted numerous experiments determining the digestibility of feeds. Schneider, 1947, has compiled 900 references covering 11,000 digestive trials. In this compilation the percent of digestion of each component of the feed; crude fiber, crude protein, nitrogen free extract, and ether extract has been listed. Also the total digestible nutrient (TDN) value of the feed is given. Schneider also compared a listing of the moisture free percentages and the total digestive nutrients.

Similar information is given by Morrison, 1956, although the listings are not converted to a moisture free basis. Morrison prefers to use the total digestible nutrients method rather than the metabolizable energy value to determine the value of the feed. He states that the metabolizable energy values are difficult to determine experimentally. Some authorities have advocated the computation of metabolizable energy values from the amount of the digestible nutrients by the use of various factors. The values usually listed for metabolizable energy may be only approximate calculated values.

Morrison also gives the value of the feed in terms of estimated net energy. This listing is included because he felt that it was possible to evaluate the more important feeds more correctly on a net energy basis than by using the values for total digestible nutrients. The estimated net energy values given in his table have been compiled or estimated from experiments primarily for growing and fattening livestock.

The value of feeds is described by Crampton and Harris, 1969, in terms of digestible energy, total digestible nutrients, and also in terms of metabolizable energy. These authors also include the usual proximate analysis. Digestible energy can be calculated from TDN values by using the formula:

$$DE(Kcal/kg) = \frac{TDN(\%)4409}{100}$$

Physiology and Internal Energy

Kleiber, 1961, states that the rate of food intake is one of the best regulated animal functions. This close regulation implies that food intake must be controlled by some physiological system. However, the utilization of energy absorbed by the body apparently varies as a function of many factors including energy level, types of feed, and type of product produced. Food intake and ultimate use of metabolizable energy (ME) appear to be related by control mechanisms within the animal's body. The literature on these two topics is summarized.

Food Intake

According to Blaxter, 1962, one of the main factors in food intake of ruminants appears to be ration quality. When sheep were given forages of different types there was a close relationship between the amounts consumed per kilogram of metabolic size and the digestibility of the energies the foods contained. The same broad generalization was also reported with subtropical grasses in Australia. Sheep on pasture of poor digestibility consumed less than half the daily basal expenditure while sheep with good quality dry matter ate considerably more than was required.

The reason for association of food intake with food quality may be related to the rate at which the food is fermented and leaves the rumen. Blaxter, 1962, states that foods pass through the gut at rates proportional to their qualities. He further contends that sheep tended to eat to constant fill irrespective of the ration they were given.

A curve of voluntary intake of food plotted against apparent digestibility of food is also presented by Blaxter. A second curve showing an estimation of potential production in terms of energy retention plotted against apparent digestibility of food appeared to be validated by experimental data.

Montgomery and Baumgardt, 1965, have found that there appears to be a linear relationship between increased energy density of the feed and total energy intake by the animal, until a certain level of energy is reached. At this point, the animal will eat to maintain the same energy level even though the energy density of the feed may increase. This relationship is shown in Figure 8.

It is generally accepted that the hypothalamus is concerned with the regulation of appetite. However, especially in ruminant animals, there appears to be disagreement as to the precise mechanism of the control. Chemostatic regulation has been proposed as the control

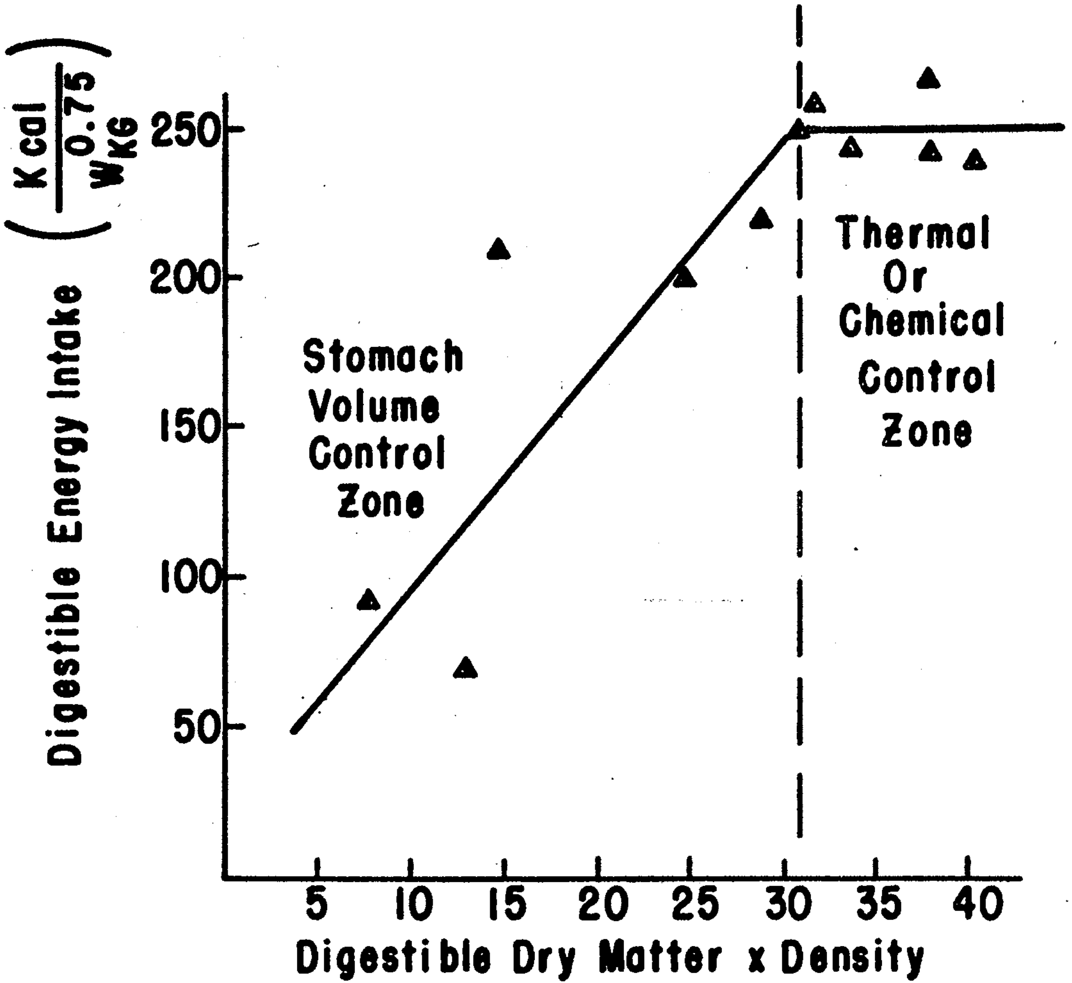


Figure 8. Relationships between digestible dry matter intake and nutritive value of feed.

method in man and other simple stomach animals, because of the relation of glucose concentration to food intake. However, Balch and Campling, 1962, report that with ruminants, infusions of glucose in large amounts over a long period of time has no affect whatever on the daily intake of food. Other metabolites, for example ammonia and acetate, do reduce food intake, but the receptors that might detect these metabolites have not been located.

Another chemostatic system as proposed by Kennedy, 1966, is based upon lipid regulation. However, proposals of control mechanisms involving responses to changes in body fat do not explain why beef cattle may have more fat than dairy cattle at the same energy intake level.

A thermostatic control mechanism has also been proposed by Brobeck, 1960. This proposal is based upon observations that eating appears to be a response to a rise in heat production. This theory is attractive because there are thermal receptors in the hypothalamus area. Also experiments by Anderson and Larsson have shown that eating stopped when the hypothalamus was warmed and begins when it was cooled. Kleiber, 1961, presented data to support his contention that cattle in warm environment controlled their feed intake in response to the heat values of the feed rather than total energy.

Metabolizable Energy and Its Utilization

Metabolizable energy can be considered to be that energy input that can be used by the body to meet its metabolic requirements. The metabolizable energy is usually considered to include the heat produced by food digestion because this heat, absorbed into the body, can be used to keep the animal warm if necessary.

The heat produced by food digestion of micro-organisms in the rumen can vary appreciably. This makes a precise estimate of the heat of fermentation an extremely difficult task. However, Blaxter indicates that the range is probably from 3 to 12 percent of the energy of the food. The usual percentage of heat produced by fermentation is estimated to be more than 6 percent.

Variations in the net utilization of the metabolic energy appears to be related to the variations of the end products of the fermentation in the ruminant. The efficiency of energy conversion to animal tissue has been related to the molar proportion of acetic acid in the rumen. The efficiency of energy retention decreases as the proportion of acetic acid in the rumen increases. Forages tend to produce more acetic acid than high grain rations.

The concentration of acetate in the blood in response to eating was reported by Simkins, Suttie and Baumgardt, 1965. They showed an increased concentration of acetate until eating stopped and then a slow return to a stable concentration which was maintained until eating started again. These data were used during the development of the chemical section and eating control module.

There is a linear relationship between metabolizable energy (ME) input and net utilization by the body. This conclusion is summarized by Reid and Tyrrell, 1968. However, the net utilizability for ruminants varies with the physical nature of the feed. Pelleted, finely ground hay has a 25 percent higher utilizability than long hay. For this reason ruminants have a net utilization of metabolizable energy that varies from 30 to 60 percent for forages and from 50 to 63 percent for long hay. The linear relationship between ME input and net utilization changes slope at the energy input level which matches the maintenance energy demands of the body.

In 1963, a new system of expressing energy requirements and feed values was introduced by researchers at the University of California. Lofgreen and Garrett, 1967, 1968, explains the procedure used to develop values for the net energy of feeds. The net energy of the feed is divided into two levels. The net energy for maintenance (NE_m) and the net energy for production (NE_p). The net energy for maintenance is defined as that amount of energy which is equal to the heat produced by an animal with no feed intake. The amount of feed required to just maintain an animal in energy balance will be a NE_m equal to the amount of heat which would have been produced at no feed consumption.

They defined net energy for production (NE_p) as the energy stored in new body protein or fat brought about by addition of feed above the maintenance requirement. In the development of this sytem and in the application of results of field trials, the authors used the metabolic body size ($W^{0.75}$) as the weight function for computations.

Biochemical Relationships

When viewed from the biochemical vantage point, all of the energy absorbed by a body is reduced to small molecules which are used as building blocks for growth or are oxidized for energy. In ruminant animals the main source of energy, comes from propionic and acetic molecules. These molecules can enter into the mitochondria and be consumed by the Krebs cycle to furnish the necessary energy. Digested protein also is broken down into its component amino acids and then reassembled as needed by the body. Assuming the proper protein balance of the ration, the energy represented by protein goes primarily into growth. The carbon skeletons of that protein consumed for energy arrive at the Krebs cycle in the form of carbon chains of two or more carbons. Therefore, basically, the ruminant animal has available two major carbon sources of energy, higher carbon molecules of propionic acid and protein and two carbon molecules of the acetic acid. Lehninger, 1970, reports that the primary stimulator for fat growth is a high concentration of acetyl CoA in the extra mitochondrial protoplasm. In fact, acetyl CoA appears to be a major switching element for several biochemical pathways. High acetyl CoA concentration stimulates growth, lower concentrations of acetyl CoA stimulate catabolism to secure the necessary energy for life.

The production of fat begins with acetyl CoA and requires input energy in the form of two NADPH molecules and one ATP molecule for each molecule of acetate attached to the fatty acid chain. When propionate and acetate pathways are traced through the Krebs cycle as is shown in Figure 9, the acetic acid molecule cannot result in net growth of protein or glucose. Two carbon atoms are lost in carbon dioxide before the molecule reaches a point in the Krebs cycle where it can exit in the synthesis pathways. Also the shunting of acetate directly into fatty acid appears to be impossible if acetate were the only energy source because of the requirement for the production of NADPH. By the time that acetate reaches a point in the Krebs cycle where it can enter into a reaction to produce NADPH the two carbon atoms have also been lost.

With propionic acid and the carbon chains from the protein mole-

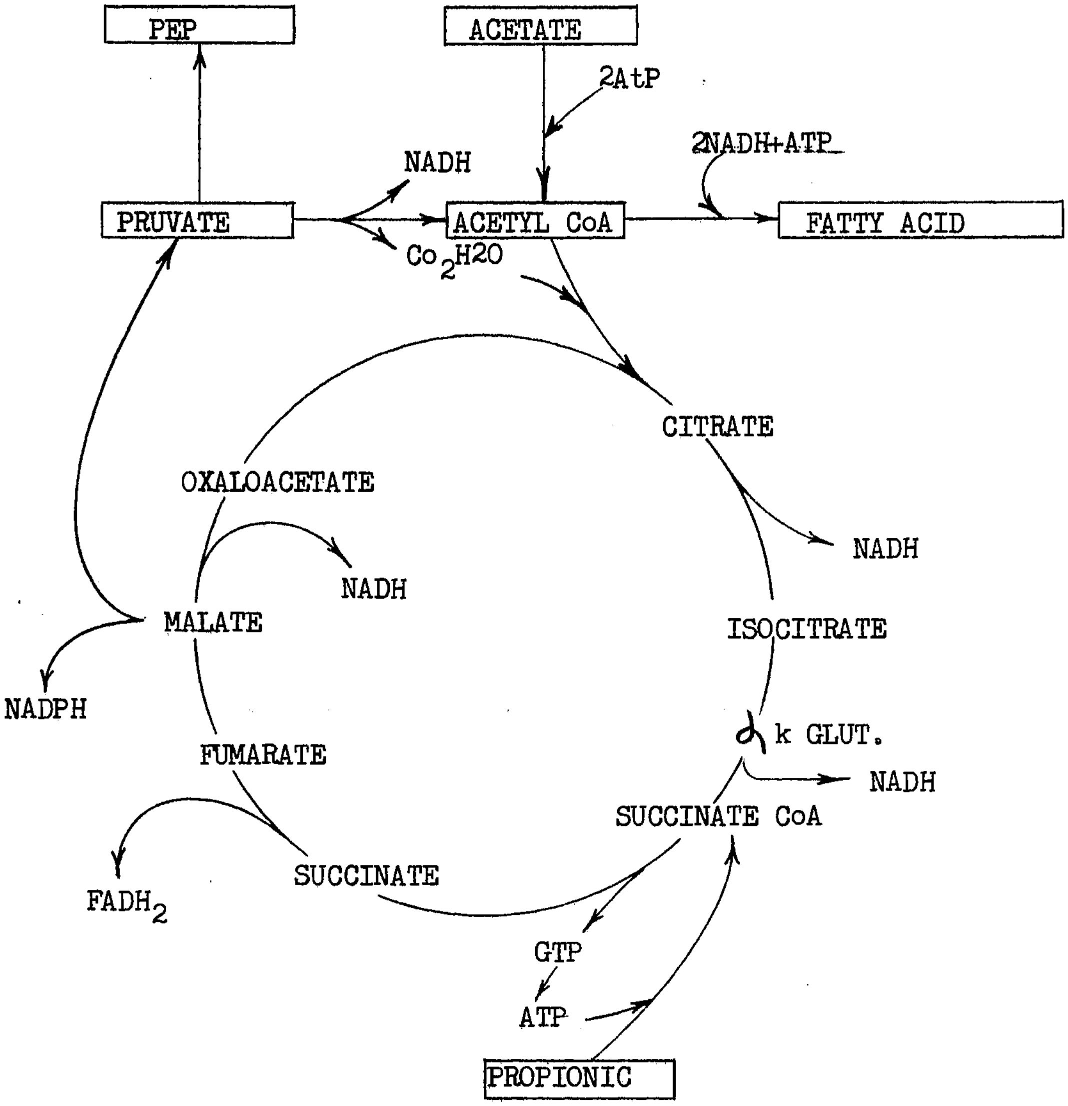


Figure 9. Pathways for synthesis of fatty acid from propionic and acetic acid molecules.

cules, the situation is slightly different. One possible reaction is catalysized by the malic enzyme, which converts malate to pyruvate plus NADPH. Tracing propionic acid through this pathway, shows that, when the molecule reaches the acetyl CoA switching point, it has generated enough energy equivalents to drive its addition to a fatty acid chain. Obviously propionic acid and other higher carbons from protein are more valuable for fatty acid growth than is acetate.

Several researchers, too numerous to cite adequately here, have done research on the acetic and propionic volatile fatty acids in the rumen and the blood. Blaxter, 1962, summarizes some of this research and presents a graph shown in Figure 10 which illustrates the decline of efficiency of fat tissue growth as the molecular ratio of acetate increases in relation to propionic acid. If the energy in the propionic acid molecules is also plotted against the molecular ratio of acetate/propionate, the net energy that goes into fat production is slightly less than the net energy available from propionic acid. Implications of this are clear, the energy represented by acetic acid molecules is available to ruminant animals only for energy and not for net production of tissue.

These biochemical relationships formed the basis for the development of the chemical section of the beef model. The CSMP implementation, essentially, simulates the action of the Krebs cycle.

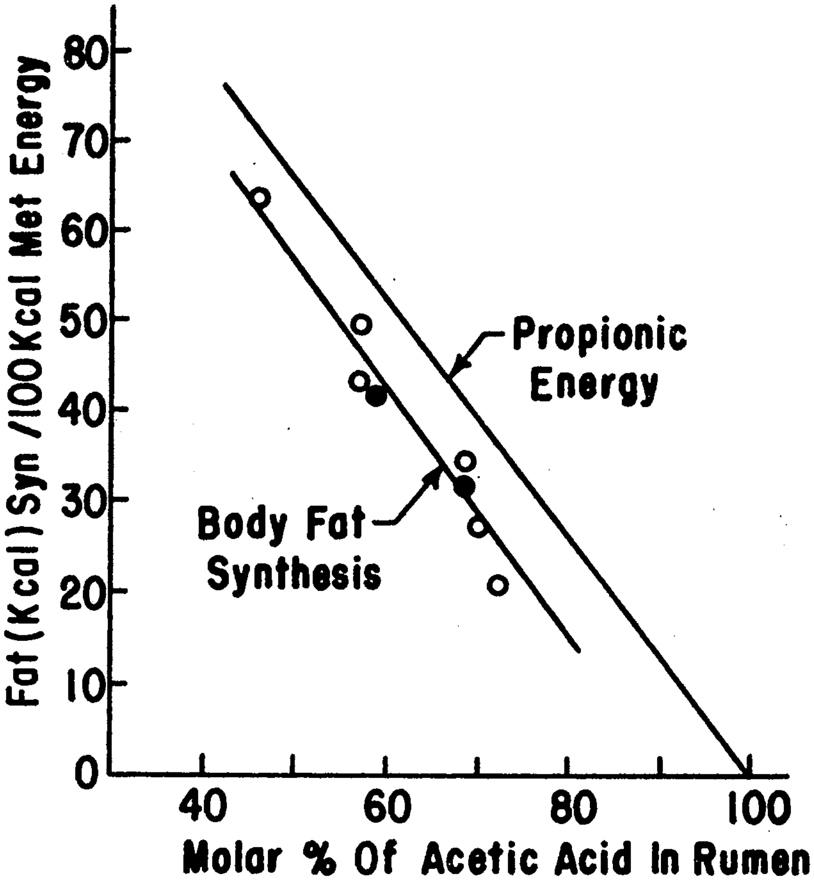


Figure 10. Plot of energy retained as fat and the energy in propionic acid as a function of the molar percent of acetic acid in the rumen.

CHAPTER III

BASIC CONCEPTUAL MODEL

Kleibers Model

The basic conceptual model considered for energy flow within a beef animal was a variation of Kleiber's hydraulic model. This variation, shown in Figure 11, is represented as a combination of three energy reservoirs with energy flow between the reservoirs.

The first reservoir is considered analogous to the stomach and intestines of an animal. Energy, in the form of food, enters the first reservoir by being eaten. This energy flow is controlled by a valve between the external food supply and the internal food reservoir. Energy leaves the food reservoir by being excreted or digested. These energy drains on the food reservoir are also considered to be controlled functions. These controls are represented by valves. For conceptual purposes, the portion of the digested energy excreted in urine or lost in gas production is combined with that energy excreted in the feces.

A portion of the digested energy is considered to be converted into a simpler chemical form more readily available for metabolic functions than food. The remaining portion of the digested energy is converted into thermal energy, a by-product of the processes required to convert food energy into readily available chemical energy.

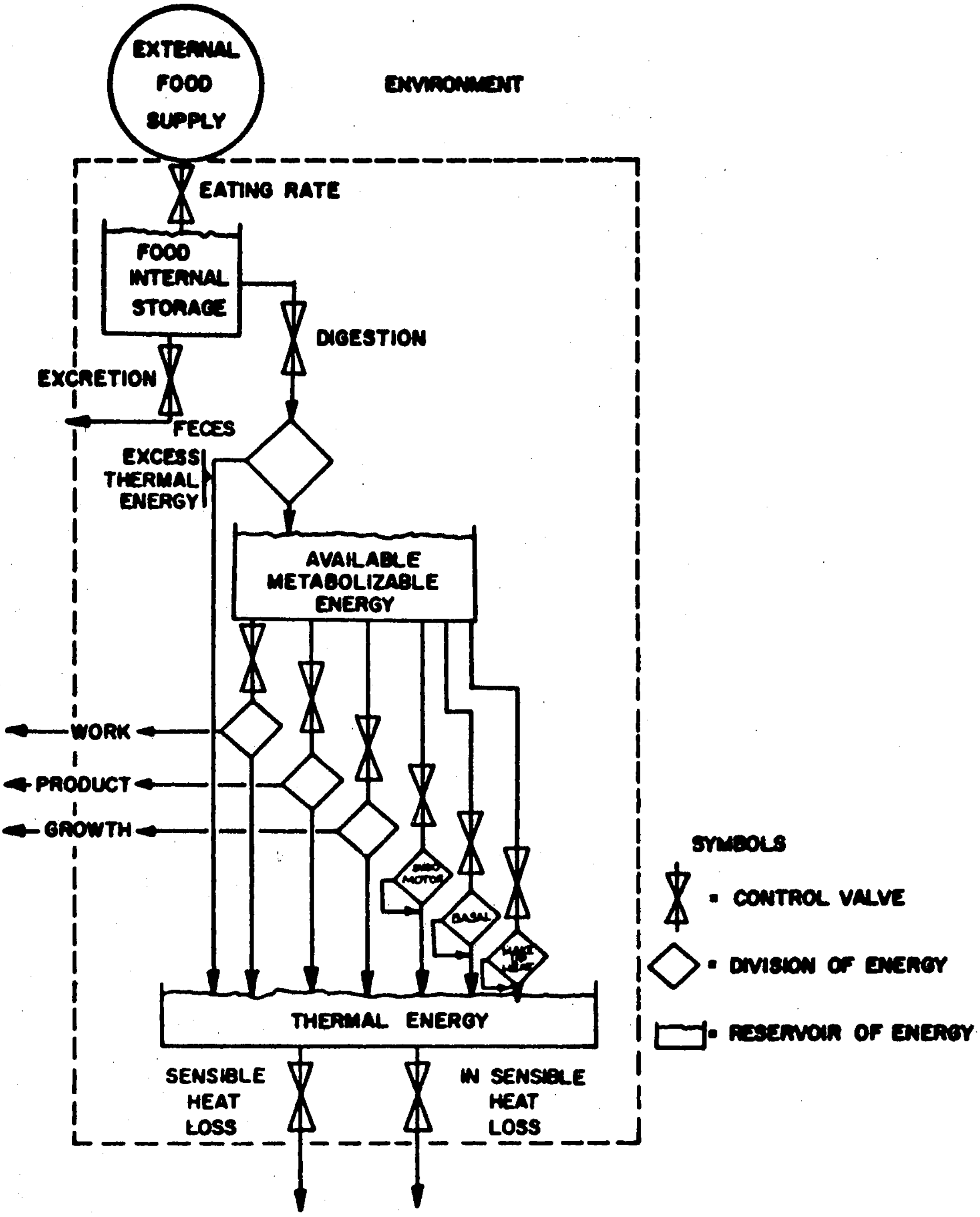


Figure 11. A schematic variation of Kleiber's conceptual model of energy utilization in a beef animal.

The energy immediately available for metabolic purposes in the body is represented by another reservoir. This reservoir is conceived as analogous to blood glucose and glycogen storage in muscle and liver. This simple reservoir holding 2-5% of the body weight represents a complex of energy storages within the body.

If necessary, an animal can create readily available chemical energy by consuming its own tissue, mainly adipose fat. This process occurs during fasting, which is considered an abnormal situation for domestic animals grown for production. Therefore, this source of available chemical energy and its control mechanisms are not included in the conceptual model.

The reservoir for available chemical energy is conceived as being drained by several energy requirements. These requirements include work on the outside world, production, growth, sudomotor work, basal metabolism expenditures for maintenance, and make-up heat requirements for temperature control.

Both the make-up heat and the basal metabolic energy requirements are considered a drain of available chemical energy which is completely converted to thermal energy. Make-up heat is created by mechanisms which produce no useful work on the outside environment. The basal metabolic rate is defined as that energy expended by a post-absorptive body at rest in a thermo-neutral environment which causes no sweating or shivering. Thus the basal metabolic rate represents the energy expended in maintaining essential life processes. All of this energy eventually becomes measurable as thermal energy transfer from a living animal. The energy to sustain basal metabolism is removed from the available chemical energy and eventually converted to thermal energy, even if there is no nutrient input into the animal and even if excess thermal energy is produced.

Each of the other demands for chemical energy also produce thermal energy due to the inefficiency of the process. This thermal energy is considered to be absorbed by the blood and tissue of the body. This absorption is represented as the collection of energy in a thermal reservoir. The thermal energy reservoir represents the thermal storage capacity of a body. The thermal level of the reservoir is indicated by temperature. This reservoir is conceived as being drained by sensible and insensible heat transfer to the environment.

Concepts of Control

The functions that control the energy exchange rates between the three reservoirs and the external environment are required to establish a valid model of animal growth as a function of nutrition, environment, age, and locomotion. Therefore, simplified control blocks are added to complete the basic conceptual model. Signal pathways and control blocks shown in Figure 12, illustrate the circuitry thought to be required for control of energy flow between energy storage reservoirs.

Homeothermic animals attempt to maintain a constant body temperature. The signals derived from small variations of the body temperature drive biological mechanisms which alter the heat loss rate or increase the generation rate of thermal energy in the body. These signals also apparently affect the nutrient intake rate. Therefore, one of the essential elements of energy control is a temperature controller.

The temperature control circuitry shown illustrates the essential

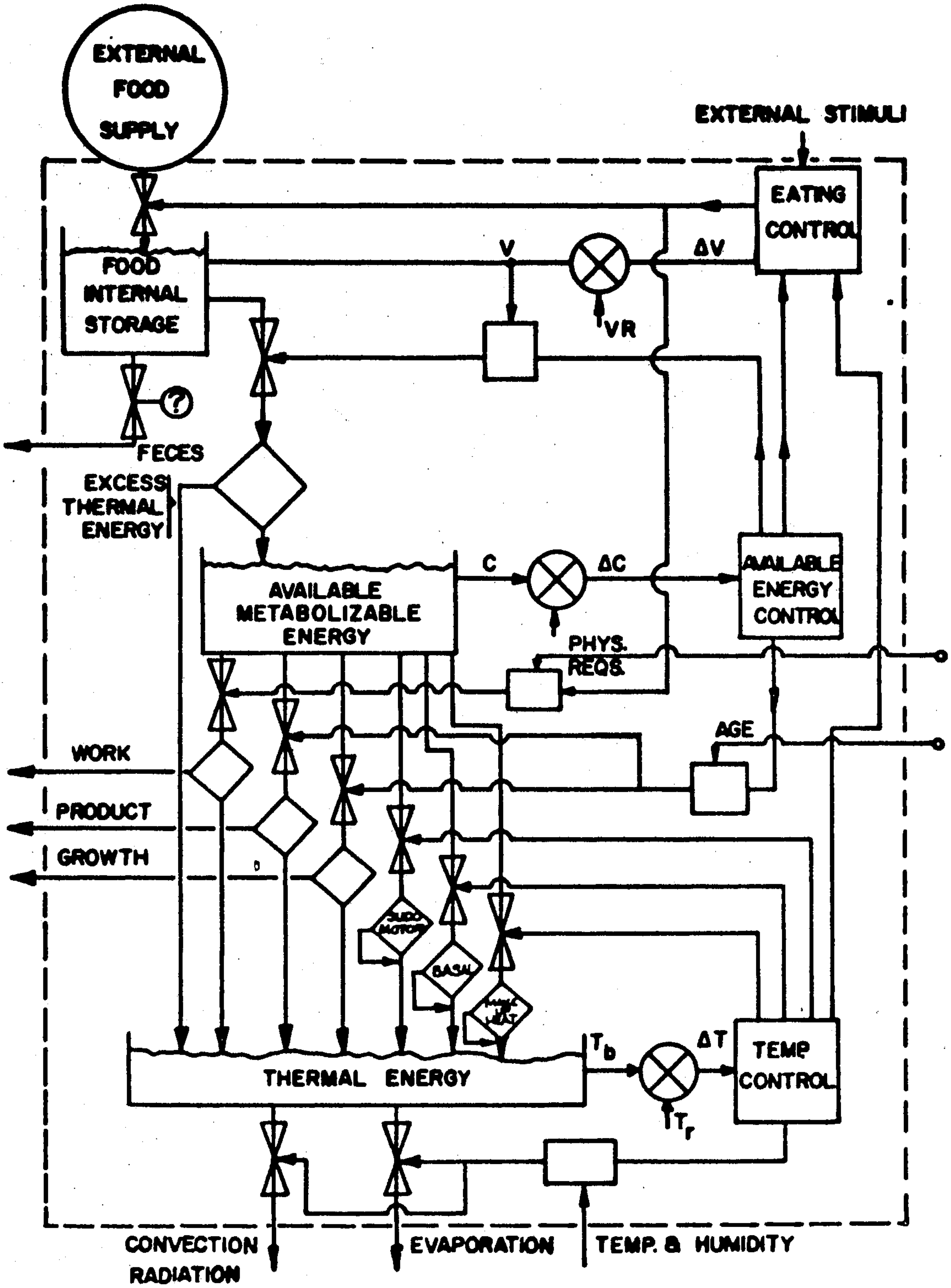


Figure 12. Conceptual relationships of energy control modules within a beef animal.

features of elaborate mathematical models which were already developed. The temperature control center, the hypothalamus of an animal, is represented as adjusting energy flow rates to prevent the deviation of the body temperature from a "set point" temperature. The temperature controller, in conjunction with ambient temperatures, is considered to control the heat loss from the thermal energy reservoir, using physical regulation mechanisms such as sudomotor, vasomotor, pilo-erection, pulmonary ventilation and huddling. If necessary, the temperature control can also activate shivering mechanisms or metabolic functions to produce make-up heat required. The temperature control center is also thought to control the basal metabolic rate.

Conceptually, the temperature controller adjusts the energy requirements for the sudomotor activity and pulmonary ventilation. When an animal becomes too warm, the lung ventilation rate increases and the animal sweats to make possible increased thermal energy transfer. These actions use available chemical energy and create additional thermal energy that must be lost by the body. Therefore, the sudomotor effect is represented as a contributing factor to the thermal energy reservoir. For simplicity, the pulmonary ventilation is not illustrated. Increased heat transfer is represented by temperature controller adjustment of the heat loss valves.

The primary indicator of available chemical energy is considered to be the blood glucose level. Blood glucose concentration also appears to be one of the controlled functions in an animal. The control of the blood glucose is accomplished by the exchange of chemical energy between the liver, muscles, and fat in the body. This complex relationship between the energy storage areas in the body and blood glucose has not been studied as completely as the thermoregulatory system.

The signals used to control the available chemical energy are considered to be related to the change in blood glucose concentration. In Figure 12, the controller for available energy is represented as adjusting growth and production depending upon the energy available. The age of the animal is also thought to be a controlling factor for these two energy requirements. The adjustment of digestion rate in conjunction with the volume of food in the intestines is also considered a function of the controller for available energy.

The eating control center is thought to receive signals from the temperature control center, the available chemical energy control center and also from the stomach. The control of food intake is considered a function of the stomach volume available, the level of blood glucose, and the body temperature. The eating control center is, therefore, represented as adjusting the food intake rate in conjunction with environment and other external stimuli.

Validation of Kleiber's Concept

The feasibility of using the concept of energy flow between reservoirs was examined qualitatively by assembling an analog computer circuit of the proposed model. This analog circuit, shown in Appendix A, used the entire capacity of the small computer available. The lack of mechanical capacity in the computer required the omission or alteration of several of the biological functions and the use of simple circuitry.

However, the mathematical model represented by the simple analog circuitry could be adjusted to illustrate energy flow rates reported by Kleiber, 1961. Control of the food eaten was obtained by a feedback signal that reduced stomach capacity as a function of excess thermal energy. The analog circuit could also illustrate, qualitatively, the effects upon nutrient requirements by changes in the thermal efficiency of the feed or thermal environment. An example of the output from the analog model is shown in Appendix A. The analog model maintained the thermal energy reservoir near the set point temperature and was able to dispose of the excess thermal energy.

Kleiber's model was then programmed using the CSMP routine on an IBM 360/65 digital computer. The programming for the CSMP routine was accomplished directly from the conceptual circuitry shown in Figure 12. Essentially, the first simulations by CSMP verified the results obtained with the analog computer.

The first simulations, done by the analog computer and by the CSMP routine, were based upon a volume control function for the amount of food eaten. As indicated in the review of literature, there appeared to be other types of control besides stomach volume. Therefore a second variation of Kleiber's model was attempted, utilizing only thermal control for the amount of food eaten. This version of Kleiber's model, attempted only by CSMP, maintained the weight of the stomach contents closer to reality and also illustrated energy flow rates reported by Kleiber, 1961. These achievements indicated the potential of continued investigation of Kleiber's basic model.

Transitional Comments

Upon examination, Kleiber's model of energy metabolism in beef animals was re-divided into four major energy storage reservoirs. Tissue growth also can represent a storage of energy. Thus, conceptually, the master flow chart could be divided into four energy sections for food digestion, available chemical energy, tissue storage, and thermal state.

For convenience in understanding the relationship of the sections to each other, the master flow chart is shown in Figure 13. This is a horizontal illustration of Kleiber's basic model. The four sections, associated with the four energy storage reservoirs; digestion, chemical, growth, and thermal, are easily identified. Energy enters the model on the left and flows as indicated by the solid lines through the energy storage sections to exit as either thermal power or animal weight. Environment inputs to the model are shown injected from the bottom. The control blocks and control signals represented have a different configuration than those shown in the diagram for Kleiber's basic conceptual model. A growth control, not clearly identified previously has been added to the growth section. The chemical controller of the basic model is now represented as the basal metabolic control. Another major addition is the composition block in the growth section. This block represents those quantities that must be empirically related to weight, such as skin area of the animal. These physical quantities are shown as dotted lines leading back to the appropriate control blocks or energy storage blocks. The primary variables connecting each block within the complete model are shown on the master flow chart in the names that are used in the CSMP listings.

Those physiological quantities that serve as forcing functions for energy control are represented by dashed lines. These quantities

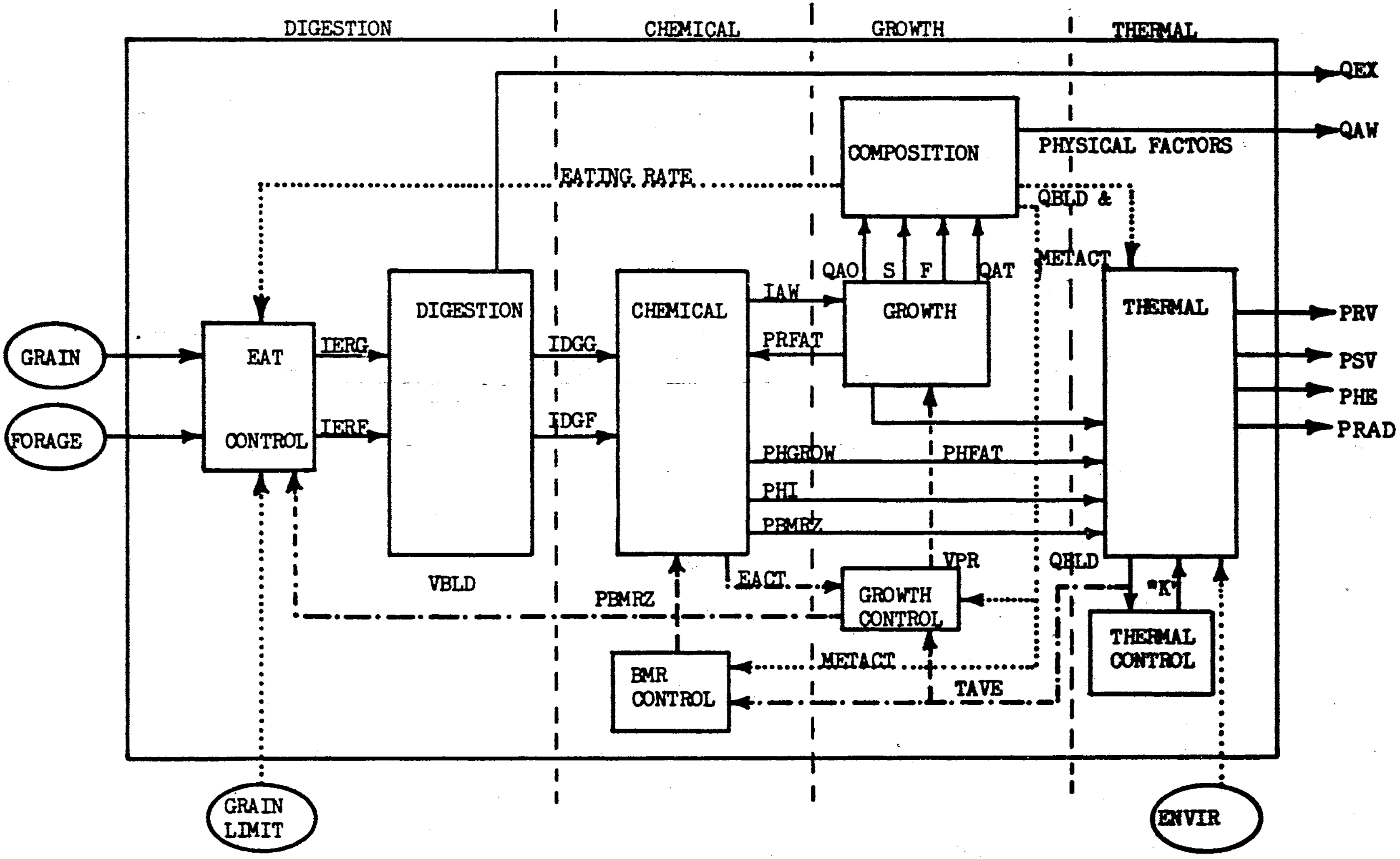


Figure 13. Schematic diagram showing interconnections and major modules of complete beef model.

include; the average body temperature, TAVE, variables associated with the acetate concentration in the blood, VPR and VBLD, and the control variable for basal metabolic rate, PBMRZ, which can be considered analogous to thyroxine concentration in the blood. All of these variables represent known physiological quantities that have been associated with energy metabolism.

CHAPTER IV

GROWTH SECTION

Investigation of Growth As A Function of Energy

The evidence reported in the literature indicates that the skeleton, muscles, and fat develop at different rates and that skeleton development takes priority. Therefore, the growth rates of these three components were examined individually.

P'alsson and Verges, 1952, reported data on the growth of the individual tissues in lambs as a function of the input energy. However, the data points at birth, nine weeks, and forty-one weeks did not establish definite curves.

The skeleton growth curves for those lambs fed a high level of energy resembled the response of a heavily damped, second order system to a step input. Therefore, an attempt was made to find a second order equation that passed through the data points available. The final weight of the skeleton was used as the forcing function. The results of this attempt is shown in Figure 14. The equation for the skeleton growth of the animal fed a high level of energy,

$$\ddot{S} + 16.5\,\dot{S} + S = 7200$$

appeared to be reasonable because the forcing function required was within 10% of the final skeleton weight. The same forcing function could be used with a larger damping factor to fit the skeletal data

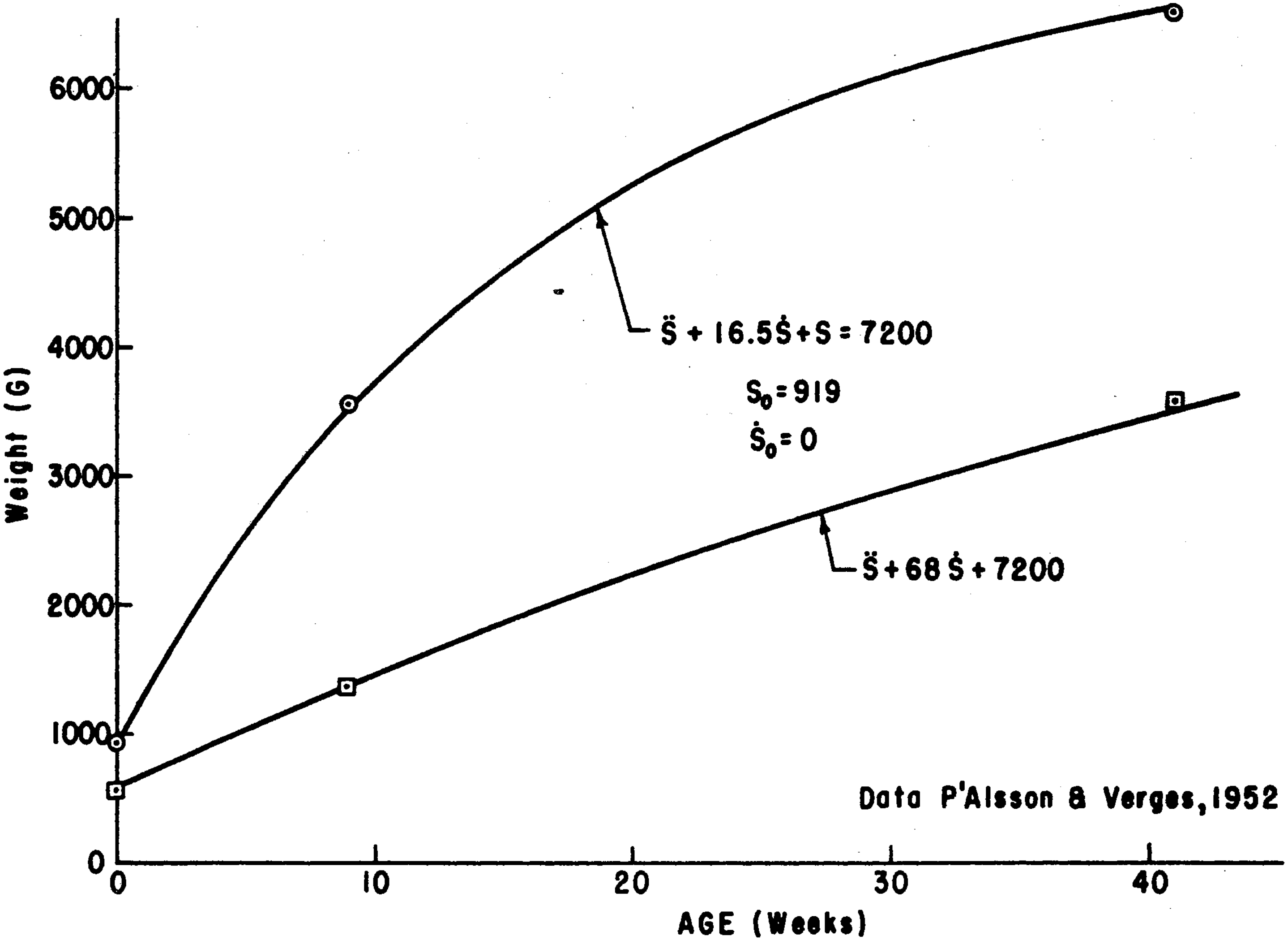


Figure 14. Analog solutions for second order differential equations that pass through the skeleton growth data of lambs.

from the animals fed a low level of energy.

A similar curve for muscle development was achieved for those animals fed a high level of energy. See Figure 15. But for the muscle growth caused by a low level of energy, a second order system, no matter how heavily damped, could not pass through the data points.

As shown in Figure 16, an attempt to use a second order model for the growth of fat was also unsuccessful. Neither the high level nor the low level of energy resulted in data that could possibly fall on a curve represented by a second order system.

Diagrams of Growth Model

At this time, Witz, 1971, took over the development work on the growth section of the model. During this development, Witz was able to demonstrate that meat tissue and fat growth could be modeled as second order differential equations using skeleton growth as an input to the meat tissue growth section and the growth of meat tissue as an input to the fat growth section. An over all block diagram of this concept is shown in Figure 42, Appendix B. An input signal, related to energy density, drives the system for offal growth and for skeleton growth. The tissue development is driven by the weight of the skeleton as well as the input energy density. The fat growth is a function of the weight of tissue as well as the energy density input.

Witz did an extensive job of collecting data on the composition of beef animals and optimizing these second order systems to match the data reported. During this development the growth circuits were refined several times. The circuits shown in Figures 42, 44 and 45 of Appendix B are the culmination of Witz' effort. These flow diagrams and the

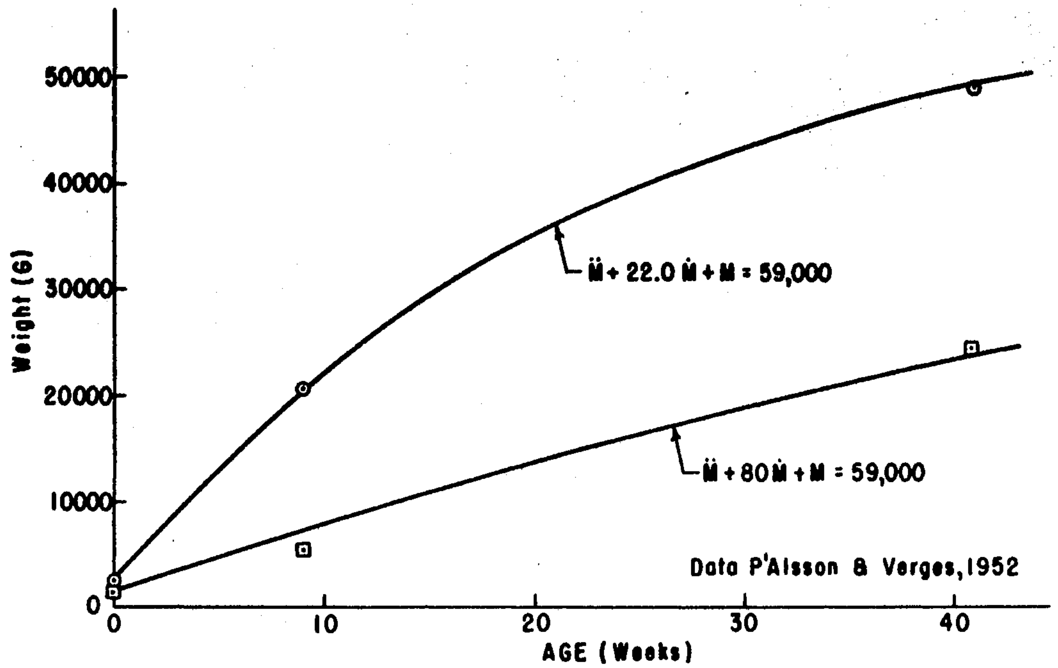


Figure 15. Analog solutions for second order differential equations that approximate the data for meat tissue growth of lambs.

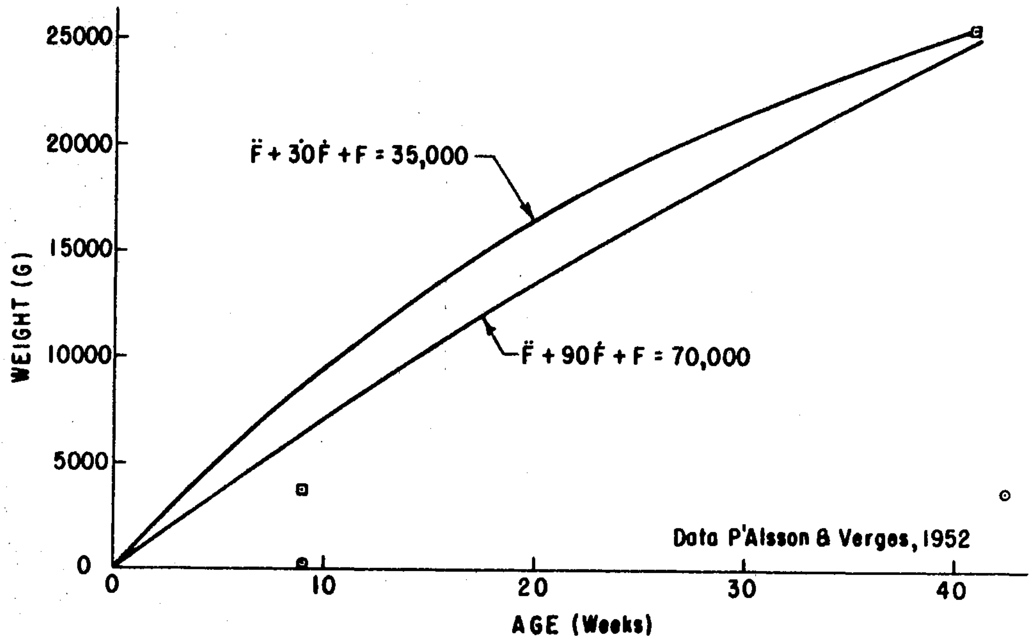


Figure 16. Analog solutions for second order differential equations compared to fat growth data.

CSMP statements to implement these diagrams are included here to make possible the discussion of the complete model. The interested reader is referred to Witz, 1971, for more detail.

The model used for fat growth is shown in Figure 46, Appendix B. Here again, the major development was made by Witz. However, an additional circuit was added to enable the mathematical model to utilize fat for energy if necessary. This circuit, shown at the top of the figure is a first order lag driven by an error signal when the energy density of the blood passes below a specified set point. An inclusive or logic control in the feed back to the integral controller makes this circuit simulate the lower turning point of a biochemical substrate inhibition reaction.

Whenever the energy density of the blood, VBLD, drops below the set point the circuit begins to activate the metabolic active tissue to utilize the required amount of fat to maintain the available energy level in the body.

Growth Control

The growth section developed by Witz and the fat metabolism circuit discussed above depend upon a driving signal of energy density. For reasons discussed more fully in the chemical section, the energy potential in the form of the acetate molecules in the blood was used as the signal to drive the growth section. The acetate energy potential, EACT, was a state variable from the chemical section of the model which, when divided by the quantity of blood in the body, produced the desired signal to drive the growth section. The amount of blood in cattle was reported by Brody, 1945, as being a linear function of the animal weight. Frandson, 1966, and others report substantially the same relationship. However, there is evidence that the volume of the fluids in the body is also affected by the thermal environment of the animal. Environments with high temperatures result in increased body fluids. Because high temperature environments are usually reflected physiologically by higher animal temperatures, the average body temperature, TAVE, was used with a first order lag having a large time constant and a linear rate function to adjust the quantity of the blood as a function of the average temperature of the animal. The linear rate function to adjust blood quantity was based on data from Dale, Burge, and Brody, 1956, who reported up to 30% more fluid volume for animals in high temperature environments compared to animals in neutral temperature environments.

The growth control circuit and the CSMP statements used to implement this circuit are shown in Figure 43, Appendix B.

Typical Results of the Growth Section

Typical results of computer simulation of the weight of each component as a function of weight and of age is shown in Figures 17 and 18. These figures illustrate that the growth modules are capable of reproducing curves that fit the data.

These curves were generated using an arbitrary input signal of the rate of gain to represent energy density available for growth. This input signal was defined as the slope of the growth curve at the weights where data were available. Therefore the input signal for optimizing the growth section was not the same as that used as the forcing function for the growth section in the complete model. How-

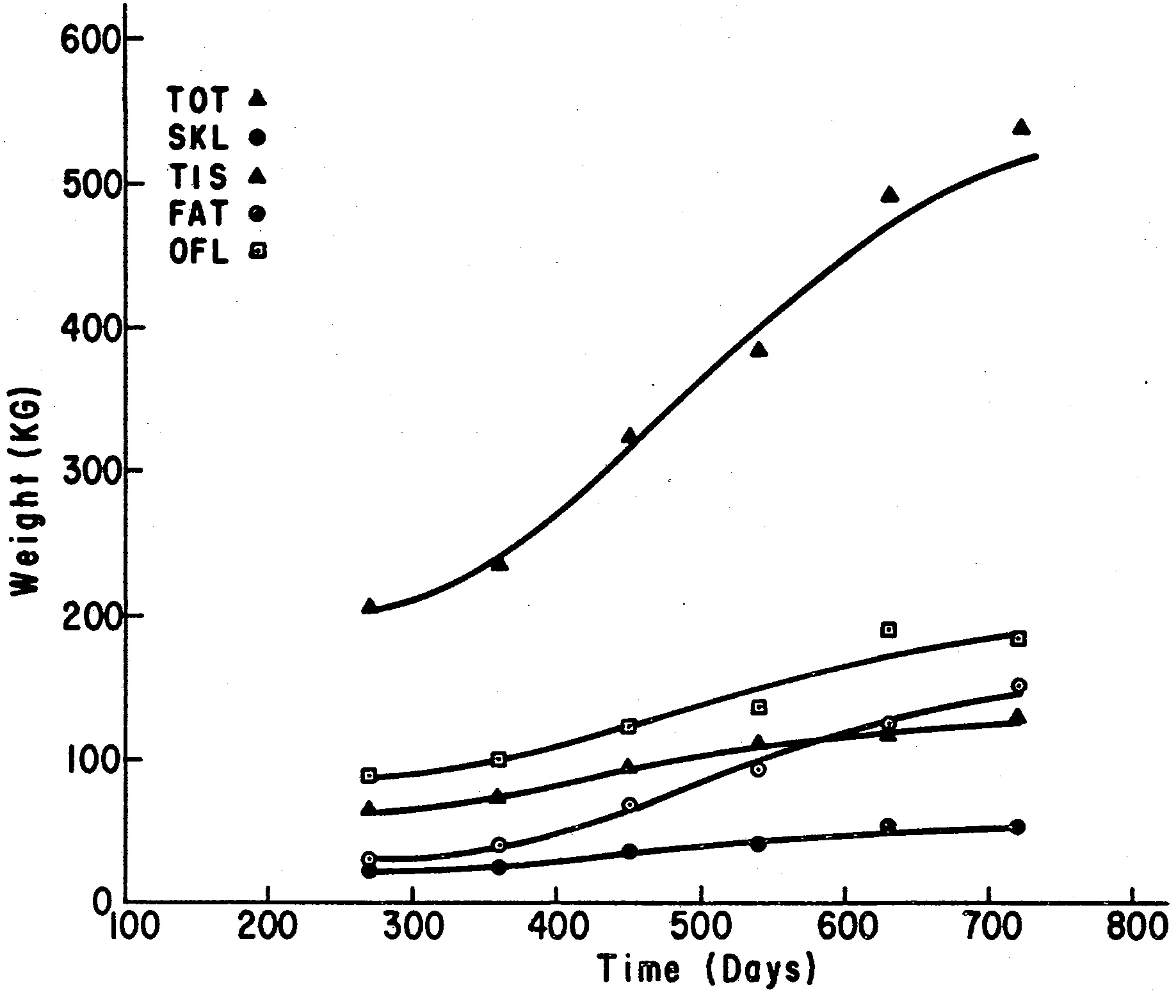


Figure 17. Simulated growth of body components as a function of time.

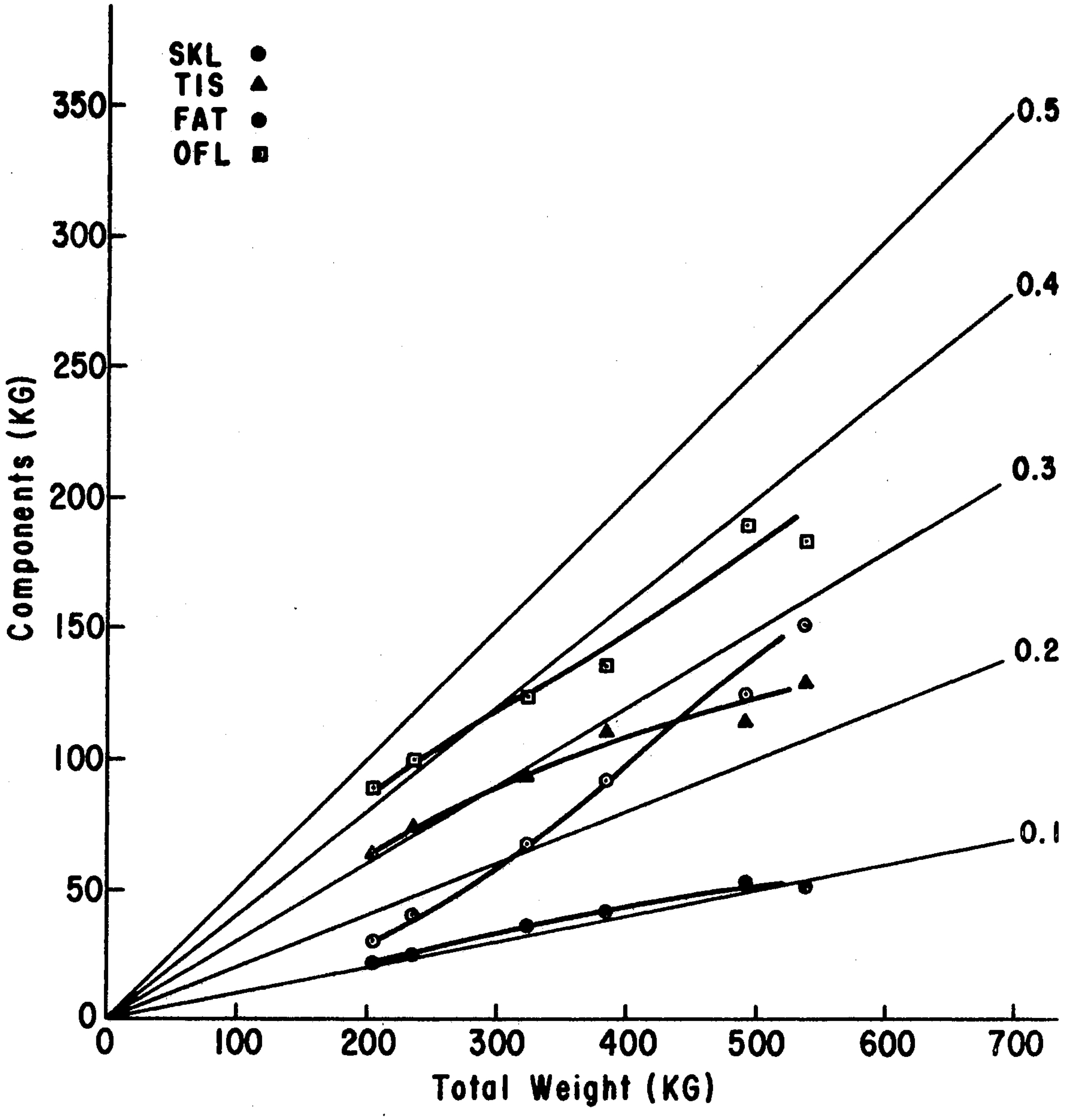


Figure 18. Simulated growth of body components as a function of the total body weight.

ever, the complete model does drive the growth section with a variable also representing energy density and it does appear to produce reasonable simulation of growth as a function of the energy of the feed. Verification of the growth sections as incorporated in the complete model is still required.

CHAPTER V

THERMAL SECTION

Physical Shape for Heat Transfer

Although valid simulation of temperature regulation in man was done by Crosbie, Hardy and Fessenden, 1961, who used a slab for the physical model, a shape more closely resembling reality was desired. Wiersma, 1966, developed heat transfer equations by assembling a model that was a composite of cylinders. His final prediction equations could be applied to one composite cylinder. Therefore, the physical shape selected as the model for heat transfer to the environment was an equivalent thermal cylinder which had the same surface area and the same internal volume as an animal at a particular weight.

The ends of the equivalent thermal cylinder could be neglected, for purposes of calculating heat transfer from humans. However, for cattle, this assumption did not appear to be acceptable. Therefore, the length and radius of equivalent cylinders transferring heat from the ends were compared to the length and radius of cylinders that transferred no heat from the ends. This comparison is shown in Table I. If the dimensions of the equivalent cylinder with heat transfer from the ends are considered, the ratio of the surface area of the ends to the area of the cylindrical surface is 0.052 at 500 kg.

$$\frac{\text{End Area}}{\text{Cylindrical Area}} = \frac{2\pi R^2}{2\pi RL} = \frac{R}{L} = \frac{20.2}{387.85} = 5.2\%$$

TABLE I

COMPARISON OF EQUIVALENT THERMAL CYLINDER CONFIGURATIONS

	RADIUS		LENGTH	
WEIGHT (KG)	ENDS (CM)	NO ENDS (CM)	ENDS (CM)	NO ENDS (CM)
150	11.72	11.33	347.82	377.67
200	13.34	12.86	357.51	384.73
250	14.77	14.20	365.01	395.17
300	16.04	15.38	371.11	403.91
350	17.21	16.46	376.22	411.45
400	18.29	17.45	380.61	418.10
450	19.30	18.37	384.45	424.05
500	20.26	19.25	387.85	429.44

Thus, the maximum error that would be made by neglecting the ends was approximately 5%. However, the equivalent cylinder was designed so that the cylinderical surface represented the total area of the animal. Because of this design procedure, the error in heat loss estimation became insignificant. Therefore, the equivalent cylinder was assumed to have only two-dimensional heat flow perpendicular to its axis.

The radius and the length of the equivalent thermal cylinder at each body weight was calculated from the area and the volume of the animal. If the surface area of the animal was not known, it was estimated by a general prediction equation for surface area as a function of weight. Volume was calculated from the weight and an estimated composite density of the animal.

If the surface area of an animal at a given weight was known, it was possible to calculate the radius required for an equivalent thermal cylinder. The weight of the animal was related to the volume in an equivalent thermal cylinder by:

$$W = \rho V = \rho \pi R^2 L$$

Where W is the weight of the animal, ρ is the density, V is the volume, R is the radius and L is the length of the equivalent thermal cylinder. The known surface area, A, of the animal was related to the equivalent thermal cylinder by:

$$A = 2\pi RL$$

Substituting the solution for L from this equation into the previous equation resulted in:

$$W = \rho \frac{RA}{2}$$

From this the radius of the equivalent thermal cylinder was

$$R = \frac{2\,W}{\rho A}$$

A cylinder having this radius and a length determined from the area equation above had the same surface area and the same volume as the animal it represented.

A sketch of an equivalent thermal cylinder is shown in Figure 19. Heat lost in the form of radiation (PRAD), convection (PHE), and skin vaporization (PSV) is shown leaving the surface of the cylinder. Heat lost as respiration vapor (PRVV) is represented as leaving the center of the cylinder. Metabolic energy is represented as being converted to

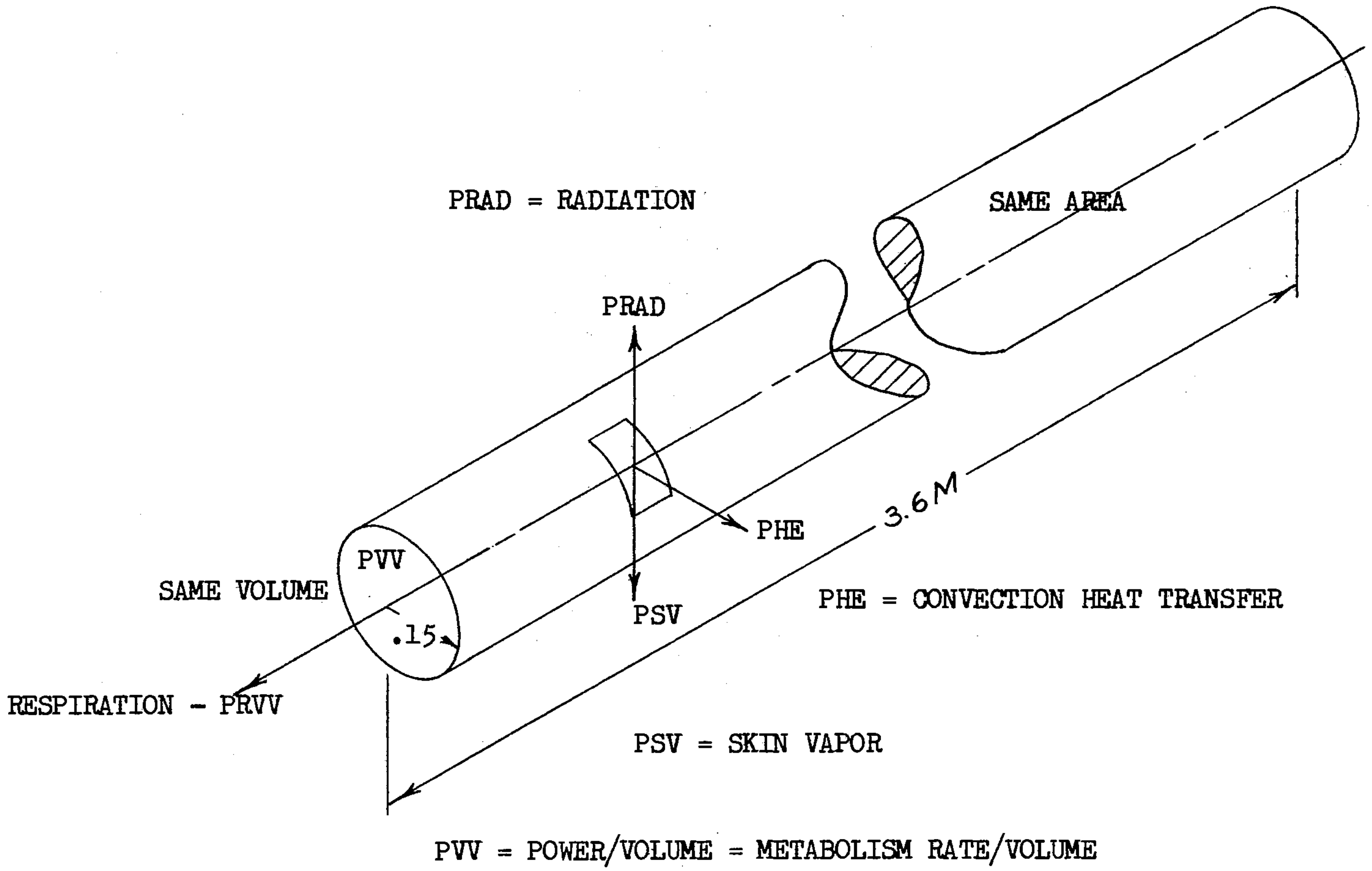


Figure 19. Sketch of the equivalent thermal cylinder for heat transfer modeling.

thermal energy throughout the volume of the cylinder. This thermal power per volume (PVV) is the energy that must be transferred for the model to maintain a set body temperature.

Dynamic Modeling of Cylinder Temperature

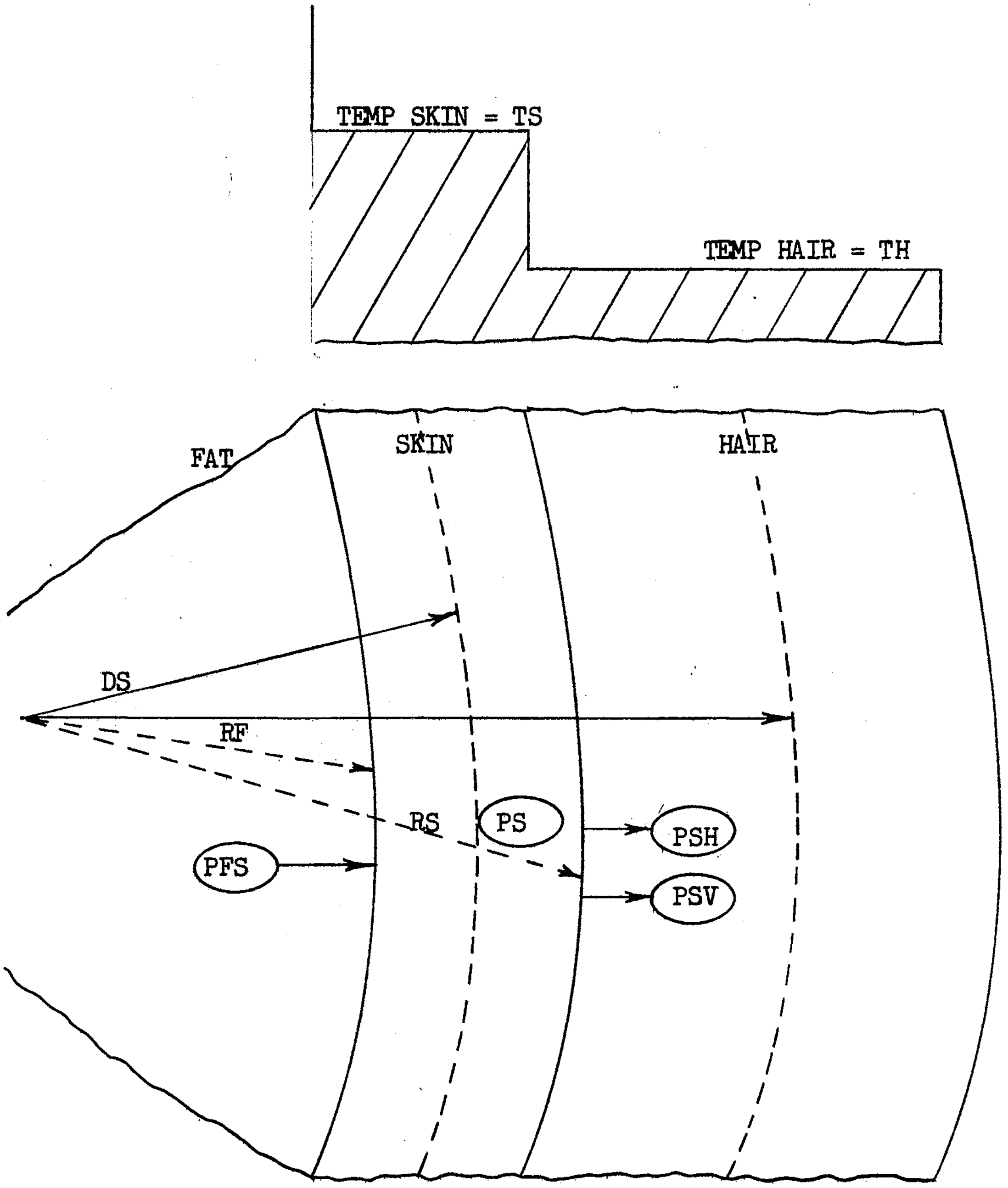
Dynamic simulation of the temperatures within an equivalent thermal cylinder requires a model using discrete rings having the same temperature across the thickness of each ring. The derivative of the ring temperature is a function of the thermal power entering or leaving and the thermal capacity of the ring. To illustrate this concept an enlarged segment of the equivalent thermal cylinder outer layers is shown in Figure 20. For a cylinder having a discrete skin thickness, the derivative of the temperature of the skin is given by:

$$\dot{T}S = (PFS + PS - PSH - PSV) / (Cp * WS)$$

Where PFS is the power from the fat to the skin, PS is the power created within the skin layer, PSH is the power leaving the skin to the hair, and PSV is the power lost from the skin as vapor, Cp is the specific heat of tissue and WS is the weight of the skin. TS is, therefore, one of the state variables in a dynamic model.

Composition Computations

The power transferred into and out of the skin element is also dependent upon the size of the cylinder, because heat transfer from cylinders is a function of the ratio of the radii to the midsection of each of the elements. The first step in thermal model development was the creation of a routine to partition the equivalent thermal cylinder into discrete rings. Rather than making a random partition, an attempt



$$\dot{TS} = (PFS + PS - PSH - PSV)/(Cp * Ws)$$

$$PSH = 2 * \pi * KH * (TS - TH)/ \ln (DH/DS)$$

Figure 20. Cross section of skin and hair elements of equivalent thermal cylinder, illustrating the formulation of the state equation for the temperature of the skin.

was made to define the equivalent cross section area of each ring to represent body components such as the gastrointestinal tract, meat, bone, fat, skin, and hair.

Data from Kleiber, 1961, were used to estimate the percentage of animal composition for skeleton and for flesh. Also relying upon Kleiber, 1961, the percentage of fat was calculated as a function of body weight.

Brody, 1945, reported the weights of various digestive organs for dairy animals from 300 to 800 kg. He also reported exponential equations that best described the organ weight as a function of body weight. To simplify programming, the weight of each organ at given body sizes was calculated. Then a single exponential equation that predicted the total weight of all organs was determined.

The resulting equation resulted in less weight in organs than could be expected from known dressing percentages. Brody's data did not include the weight of the food in the alimentary canal. Data from P'alsson and Verges, 1952, indicated that ruminant animals could have approximately 15% of the body weight as contents of the alimentary canal. When 15% of the body weight, representing contents of the alimentary canal, was added to the total weight of the organs, the sum was about 32.2% of the weight at 250 kg. This appeared to be within reason when compared to the 35.8% dressing percentage reported for sheep. Calculating the constant required to predict the weight of organs and the contents of the alimentary tract at 250 kilograms resulted in the following formula:

$$\text{Organ \& Content Weight} = 6.62\ W^{0.453}$$

Use of this composite formula at 600 kg indicated that the contents of the alimentary tract would be approximately 9%. This value also appeared reasonable when compared to the 8 (or higher) percent reported by P'alsson and Verges, 1952.

At the weights below 100 kg, the use of the composite formula appeared to predict a high organ weight. Between 200 kg and 500 kg, the composite equation appeared to be useful for calculation of weights of the organs and the contents of the alimentary canal.

The percentage of cross section area required in the equivalent thermal cylinder to represent the individual components was calculated from estimated weights of each type of tissue. Then the total cross sectional area of the equivalent thermal cylinder was subdivided into rings containing the appropriate percentage of area for each type of tissue. The radius to each ring surface was computed by an algorithm which is shown as statements 170 through 260 in Appendix D. Figure 21 shows the results of composition computations at two different weights. Hair and skin thicknesses were held constant at 0.005 and 0.0025 M respectively. These thicknesses were arbitrarily chosen and then adjusted, by trial and error, until they seemed both physically reasonable and resulted in reasonable heat transfer coefficients.

Statements 270 through 410 of the computer program listing in Appendix D were the necessary calculations required to define the physical relationships for heat transfer from the cylinder as a function of size. These physical relationships included the cross sectional area for each component so that the thermal capacity could be calculated.

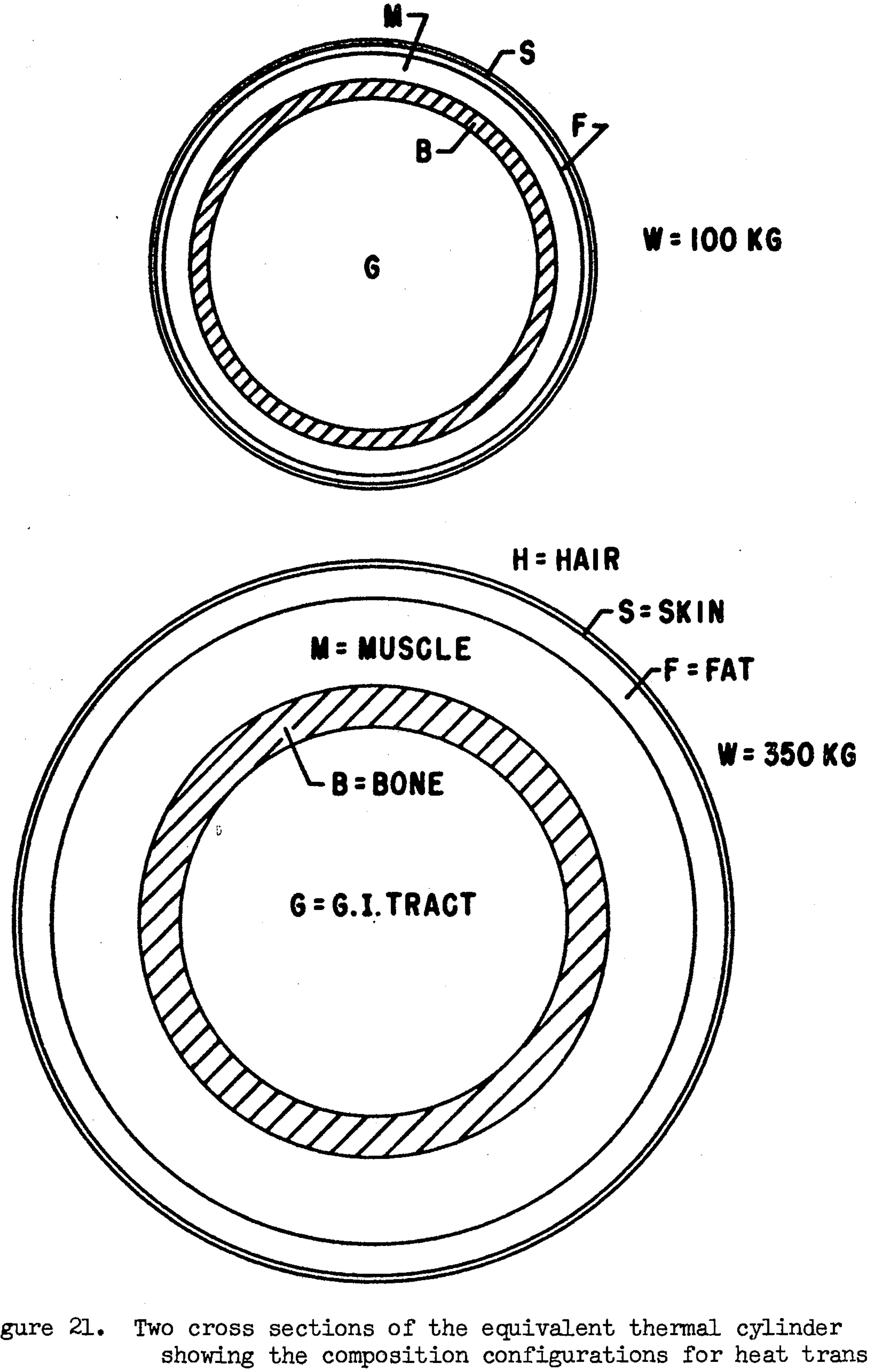


Figure 21. Two cross sections of the equivalent thermal cylinder showing the composition configurations for heat transfer calculations at two different weights.

Selection of Data to Model

Although the composition of the equivalent thermal cylinder could be computed, a solution of the steady-state temperature distribution required experimental data relating body temperatures to the power transferred from the animal as heat. The data selected as a basis for developing the thermal section of the model came from the Missouri experiments on growing beef calves in 50 and 80 F environments. In particular, the Shorthorn data was selected for the primary modeling of the thermal section.

These selections were made because:

1. These trials were the most completely documented reports of energy metabolism in growing beef animals. The data included measurements of skin, hair and rectal temperature as well as the thermal energy rates.
2. The variations due to the environment were reduced by constant environmental temperatures. The interior housing also reduced radiation and wind effects.
3. The Shorthorns, in particular, exhibited the greatest physiological differences in response to the thermal environments.

There were some acknowledged disadvantages in selection of these data for simulation. These included:

1. A limitation on the maximum amount of grain the animals could consume per day. This limitation was imposed in the middle of the experiment and resulted in a net decrease of TDN consumed by the Shorthorns at 50 F. The energy rate appeared to fluctuate as a result of the reduced TDN consumption.
2. The data did not extend to the usual finishing weight of beef animals in feed lots (500 kg).
3. The Shorthorn animals at 80 F had their hair clipped three times. This clipping disturbed the temperature relationships of the skin and hair.

Verification of Missouri Curves

Kibler, 1957, attempted to fit exponential curves to data for the metabolic rate of growing beef animals as a function of weight. However, for this study a more precise fit of this data was achieved by using a least squared fit to a polynomial equation. See Appendix C. This polynomial prediction equation for metabolic rate was used to specify the thermal energy input to the equivalent thermal cylinder during development of the thermal section of the model.

The data showing the surface area as a function of weight was apparently not reported for the beef animals in the Missouri experiments. However, for dairy animals in a similar experiment, the prediction equations for surface area as a function of weight appeared to be different than the usually accepted exponential equation by Brody, 1945. Furthermore, use of Brody's prediction equation for surface area resulted in values of heat transfer per unit area that did not correspond to the reported data. Therefore, the surface areas that must have been used were calculated from data reported by Kibler, 1957. The values computed in this study of the surface area of the Shorthorn animals are shown in Table II.

The curves for the surface areas of the Shorthorn animals as a function of weight are also shown in Appendix C, with the curves produced by Brody's equation and the equation reported by Johnson, 1961. The prediction equation reported by Johnson was the best fit of the data from animals that weighed between 50 to 400 kg, but extension of the equation beyond the data range appeared to be unacceptable. Brody's equation for surface area appeared to be extendable beyond the data range but it did not provide adequate prediction of the reported surface areas within the data range. Therefore, either the reported surface area or a polynomial equation passing through the reported data was used to define the surface area of the equivalent thermal cylinder. Above 400 kg, a modification of Brody's equation was used to determine surface area.

TABLE II

SURFACE AREA OF SHORTHORN CATTLE CALCULATED FROM DATA BY KIBLER, 1957

Animal Weight (kg)	50°F Area (m^2)	80°F Area (m^2)	Ave. Area (m^2)
50	1.336	1.386	1.361
60	1.454	1.478	1.466
80	1.695	1.679	1.687
100	1.845	1.842	1.844
125	1.971	1.994	1.983
150	2.103	2.105	2.104
175	2.250	2.243	2.247
200	2.409	2.466	2.438
225	2.585	2.864	2.725
250	2.784	3.338	3.061
275	3.007	3.694	3.351
300	3.299	4.087	3.693
325	3.654	4.304	3.979
350	4.000	4.441	4.221
375	4.339		
400	4.645		

General Prediction Equation for Surface Area

The alternative equations for surface area as a function of bovine weight were compared in detail. Brody's original equation was formulated for dairy animals. The equation by Brody and Matthews, 1928, developed from beef animal data, predicted lower surface areas than Brody's formula at low animal weights, and higher surface areas at higher weights. The prediction method of Hogan and Skouby, 1923, was also developed using beef animals. The values predicted by Hogan and Skouby for surface areas of beef animals were 6 to 7% higher than the values predicted by Brody. A constant of 0.16 instead of 0.15 in Brody's equation gave approximately the same predicted values. Because Brody's equation was simpler to use than Hogan and Skouby's method, the constant was changed to 0.16 and used for the prediction of surface areas made with Brody's equation.

Computation of Heat Transfer Coefficients

The data reported by Stewart and Shanklin, 1958, included skin, hair, and rectal temperatures of the growing calves from approximately three months to sixteen months of age. These data could be correlated to the metabolic rate per unit area as reported by Kibler, 1957. Using the simple heat transfer relationship,

$$\text{Thermal Resistance} = \frac{(T_1 - T_2)}{(Q/A)}$$

an estimate of the beef animal's body, hair and surface resistance to heat transfer was made. Thermal resistance values for all three breeds of beef animals in both environmental temperatures were computed.

These computations revealed that the animals apparently had control of the body, hair, and, most unexpected, the surface resistance to heat transfer. Furthermore, the resistance values computed appeared to be correlated with the magnitude of the thermal power transfer per unit area. Figure 22 illustrates this phenomenon. The data in this figure are for the Shorthorn animals raised in the 50 F environment. The data, as plotted, show a definite decrease in thermal resistance as the heat transfer per unit area increases. The beef animals in this study must have been able to lower the thermal resistance as required to transfer excess heat to the environment.

The conclusion that the animals controlled the surface heat transfer coefficient was further supported by the results of Wiersma's study. The heat transfer coefficient was predicted by Wiersma, 1966, to increase as the environmental temperature increased. However, the data used in the study showed a decrease in the heat transfer coefficient as the environmental temperature increased.

Heat transfer per unit area is a physical quantity that would appear to be physiologically difficult for an animal to measure. Therefore, the data from the Missouri studies was searched in an attempt to find a physiological response that could be used as the forcing function for the control mechanisms which change the thermal resistance. The only physiological variable that could be correlated with heat transfer per unit area was the pulmonary ventilation rate of the animal. However, as indicated in Table III, this variable was also considered a physiological response to a forcing function that must be related to the heat produced.

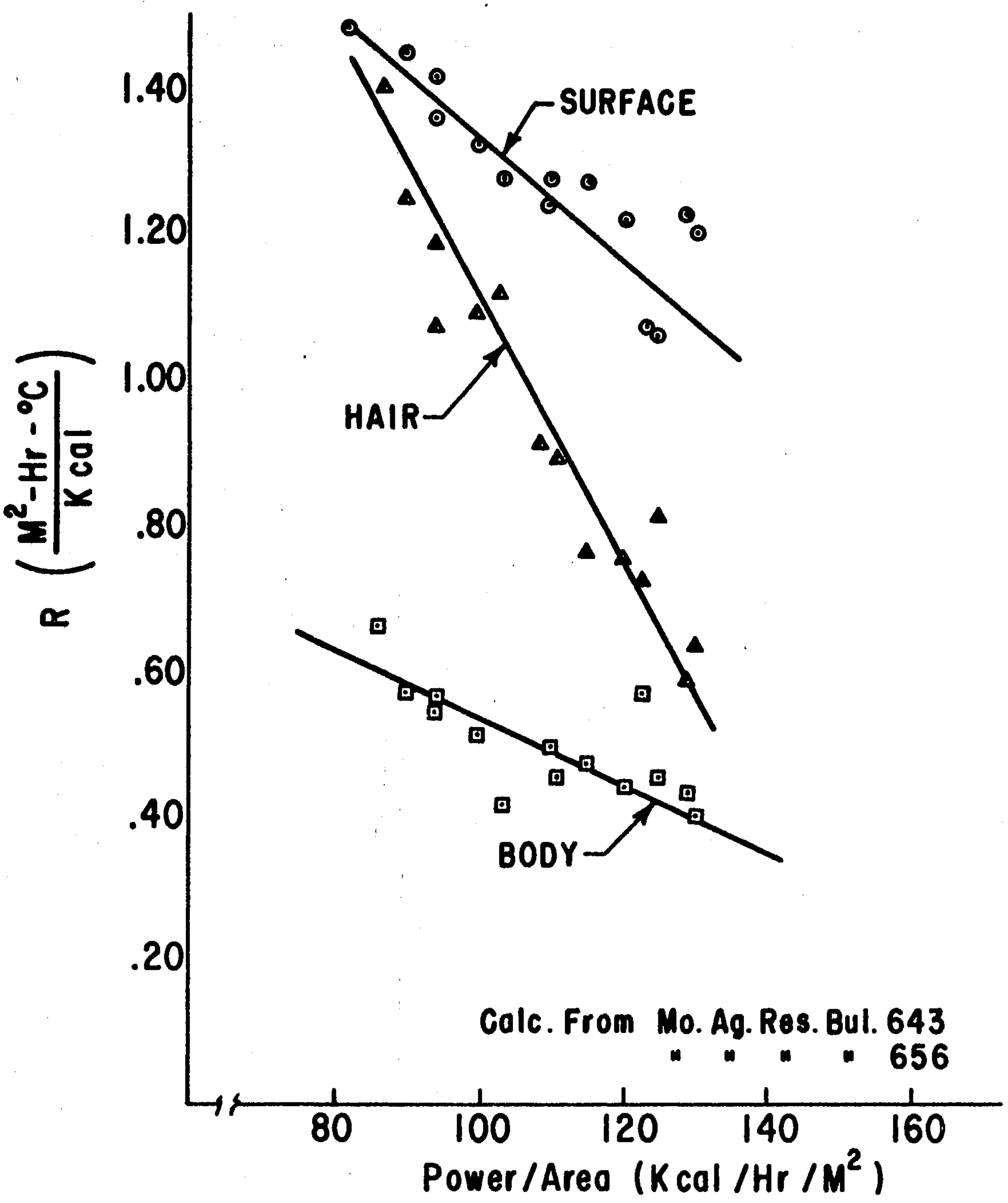


Figure 22. Relationships of heat transfer resistances to the thermal power transfer per unit area.

TABLE III

RELATION OF THE HEAT TRANSFER COEFFICIENT K TO PULMONARY VENTILATION RATE AND TO HEAT TRANSFER PER UNIT AREA

Weight (kg)	K (Kcal/M^2-Hr-^oC)	Respiratory Rates (est) (Lit/M^2 - HR)	Heat Transfer (Q/M^2 - HR)
50	1.27	1230	40
60	1.01	1300	45
80	1.20	1400	56.5
100	1.77	1500	68
125	2.16	1500	81
150	2.48	1600	77
175	3.48	1430	76
200	2.81	1500	69
225	3.19	1400	59
250	2.32	1380	48.50
275	2.04	1250	45.50
300	1.92	1150	43.00
325	2.02	1180	42.50
350	2.29	1200	44.00
375	2.43	(?)	44.50

At the end of the Missouri study, after the animals were grown at uniform environmental temperature for over a year, all of the breeds were subjected to variable environmental conditions with temperature, in some cases, up to 105 F. The data, reported by Kibler, 1957, also contain the pulmonary ventilation rate and the rectal temperature for each test in different environments. There appeared to be a high correlation between the rectal temperature of the animals and the pulmonary ventilation rate.

A multiple regression analysis was made of these data. The results indicated no significant difference due to breed, but a highly significant relationship between rectal temperature and ventilation rate. A polynomial equation of the ventilation rate as a function of body temperature was established. A third order polynomial equation fit the data accurately. The first portion of the curve from 38.5 C to 39.5 C was approximately a straight line. Using the ventilation rate reported at 38.65 C as the base, a ventilation ratio was computed as a function of the rectal temperature. This ratio versus rectal temperature is shown in Figure 23.

With this clue, the ventilation rates of the animals during their growth in the constant temperature environment was investigated. Calculations showed that the ventilation ratio of the six groups of animals (three breeds, two temperatures) also correlated to their average rectal temperature. The ventilation ratio as a function of average rectal temperature for the growing animals in constant environmental temperature is also shown on Figure 23, by the solid lines with the arrow heads pointing in the direction of rectal temperature at maximum growth. There was striking correlation between these ventilation ratios and the ventilation ratio predicted at the end of the experiment.

This correlation, of the ventilation rate to rectal temperature, indicates that the beef animal is highly sensitive to the temperature of the body. A small deviation in body temperature can cause significant physiological changes in the respiration rate. Therefore, it

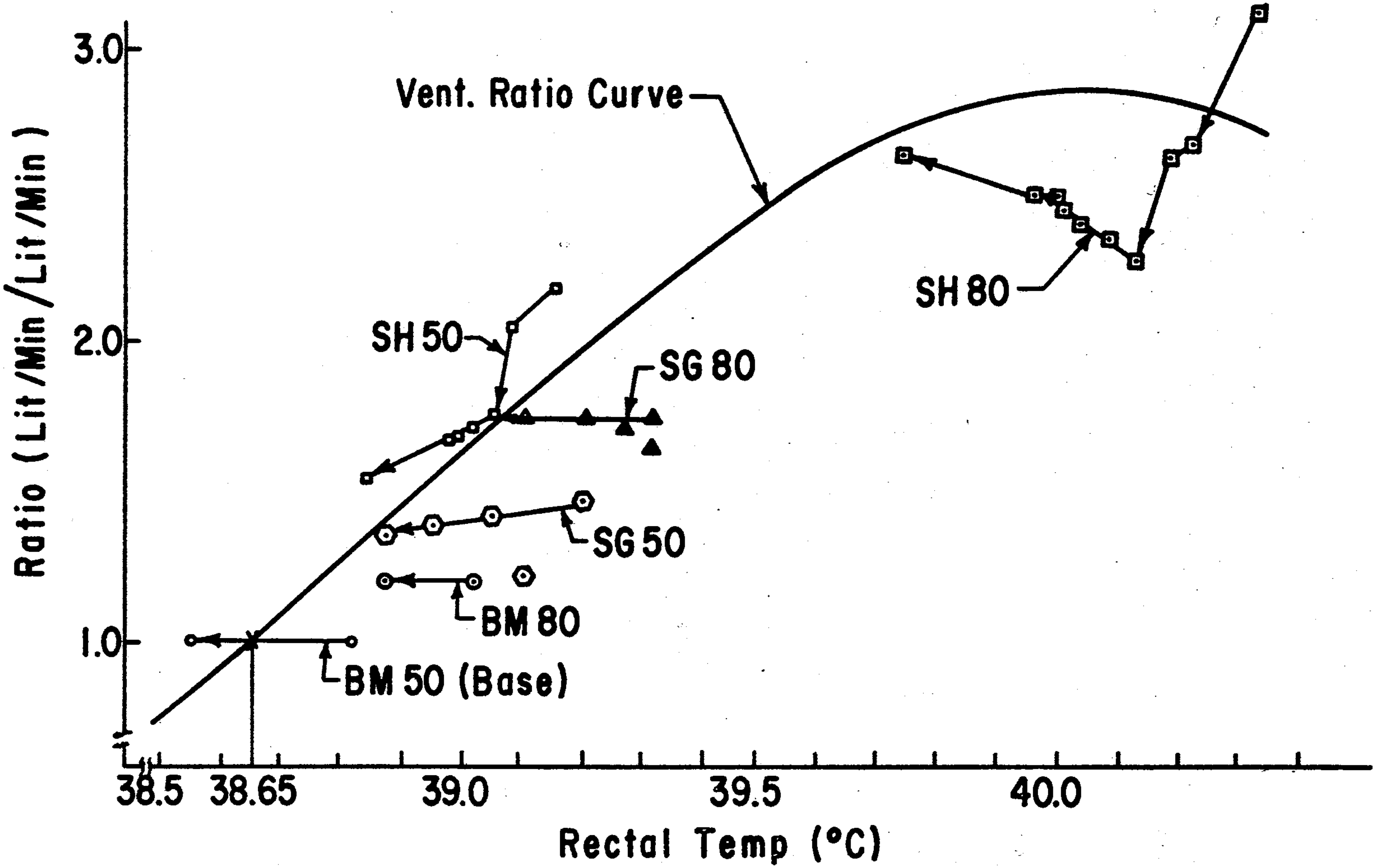


Figure 23. Plot of the ventilation ratio as a function of rectal temperature.

seemed logical that the body temperature was also the forcing function for the mechanisms that control heat transfer. For example, the surface heat transfer coefficient could be altered because of the pumping effect of the rib cage as the breathing rate changed. The ventilation rate might be a more reliable indicator of thermal state, than the rectal temperature.

Heat Transfer Values

Assuming that a suitable temperature signal could be calculated for use as a forcing function, an effort was made to establish the heat transfer coefficients. To illustrate the procedure, the mathematics for the element representing the skin layer will be shown. Similar relationships exist for each element of the equivalent thermal cylinder.

The derivative of the temperature of the skin is a function of four values; the thermal power transferring from the fat to the skin, PFS, the thermal power being created within the skin, PS, the thermal power leaving the skin by conduction to the hair, PSH, and the thermal power leaving the skin as vapor, PSV. Refer to the cross section of the skin shown in Figure 20.

The rectal, skin and hair temperatures on the growing beef animals reported by Stewart and Shanklin, 1958, were assumed to represent steady-state values. This assumption implied that the derivatives of the temperatures were zero. Therefore, the state equation for the derivative of the temperature of each component of the equivalent thermal cylinder could be set equal to zero.

$$0 = (PFS + PS - PSH - PSV) \qquad SS$$

The power being transferred from the fat element to the skin element can be defined by the equation;

$$PFS = 2\pi K\ (TF-TS)\ /\ \ln\ (DS/DF)$$

Where TF is the fat temperature, TS is the skin temperature as reported in the data, DF is the distance to the center of the fat element, and DS is the distance to the center of the skin element. The distances, DS and DF, were assumed known because they could be computed for the equivalent thermal cylinder. The heat transfer coefficient, K, and TF were both unknown.

The power being transferred from the skin to the hair can also be defined by a similar equation involving the temperature of the hair and the heat transfer coefficient, KH, between the skin and the hair. Enough data was available to compute KH directly.

The thermal power being created in the skin could be computed by the relationship

$$PS = \pi\ (RS^2 - RF^2)\ PVV$$

where RS and RF are the radii of the skin and fat surfaces and PVV represents the metabolic rate distributed throughout the cross sectional area of the animal.

Substituting for PFS, PS and PSH in equation SS and solving for (TF-TS) results in:

$$-\ (TF-TS) = \left((RS^2-RF^2)\ PVV - \frac{KH\ (TS-TH)}{\ln(DH/DS)} - PSV\right)\frac{\ln\ (DS/DF)}{2K}$$

Where PSV is skin vaporization adjusted to the equivalent thermal cylinder.

Unfortunately, this relationship does not allow computation of the fat temperature because the body heat transfer coefficient remains unknown. However, the thermal power passing through the temperature gradient (TF-TS) is equal to all of the thermal power generated within the body. Therefore, the heat transferred over the boundary of the fat and skin layer is;

$$\frac{2\pi K(TF-TS)}{\ln (DS/DF)} = \pi (RF^2-RM^2)\ PVV + \frac{2\pi K\ (TM-TF)}{\ln (DF/DM)}$$

Heat transferred to exterior element	=	Heat generated within element	+	Heat from interior element

Although this relationship does not appear helpful because TM, TF, and K are now unknown, the reasoning can be continued until the element representing the gastrointestinal tract is reached. Its temperature can be assumed to be the rectal temperature and the only heat leaving is the heat generated within the element.

The total temperature potential between the gastrointestinal tract and the skin temperature must be equal to the individual temperature potentials between each element. Therefore, an arbitrary K value was assumed and, starting with the known temperature of the gastrointestinal tract, the temperature differential between each element was calculated. The computed values were summed. When the desired temperature differential between rectal and skin was divided by the computed temperature differential, the resulting ratio was equivalent to the ratio by which the arbitrary K value had to be adjusted to result in the correct temperature potential. Then, starting again with the gastrointestinal tract, the correct differentials between each element were computed and the internal temperatures calculated by addition.

The one step trial and error adjustment of the heat transfer coefficient for a given cylindrical size is the result of the linear relationship between K and the temperature differential. Probably the heat transfer coefficient could have been computed directly from the skin and rectal temperatures, the metabolic rate, and the dimensions of the equivalent thermal cylinder. However, because the programming was necessary to compute the steady state temperatures for bone, meat, and fat, and because this approach allowed the insertion of different heat generation rates for each body component, the computer implementation of the one step trial and error solution for the body heat transfer coefficient was developed.

The algorithm to calculate the body heat transfer coefficient, K, the heat transfer coefficient from the skin to the hair element, KH, and the convective heat transfer coefficient, H, is shown in statements 500 through 790 of the computer program in Appendix D.

The entire computer program given in Appendix D which combined computation of the equivalent thermal cylinder with the algorithm to solve for the heat transfer coefficients and body temperatures made possible the computation of heat transfer coefficients that would match the individual sets of data from Stewart and Shanklin, 1958. The heat transfer coefficients calculated for 49 sets of data are shown in Table IV. During these calculations, the gastrointestinal tract and meat tissue were assigned heat generation rates of 1.0 PVV, the skeleton was assigned a rate of 0.1 PVV, and the fat a rate of 0.2 PVV. A weighted average body temperature, TAVE, was calculated from the temperatures and cross section areas for the gastrointestinal tract, the skeleton, and the meat tissue.

A statistical correlation analysis was made between the equivalent thermal cylinder variables and the thermal power transferred per unit area. All of the heat transfer coefficients calculated, the rectal temperature and the average temperature of the body had a

TABLE IV

HEAT TRANSFER CALCULATIONS

1	119.945	39.021	37.135	1.058	.033	6.351
2	125.245	38.979	36.734	.959	.040	6.674
3	129.334	38.944	36.910	1.123	.036	7.348
4	130.825	38.953	37.108	1.266	.035	7.461
5	134.681	38.979	37.509	1.684	.034	7.712
6	138.870	39.009	37.427	1.670	.036	7.944
7	144.362	39.055	36.939	1.365	.047	7.877
8	144.490	39.056	36.981	1.395	.047	7.887
9	149.487	39.066	37.221	1.717	.048	8.323
10	153.313	39.074	37.160	1.777	.065	7.522
11	156.388	39.083	37.175	1.898	.065	7.842
12	156.610	39.082	37.306	2.049	.062	7.858
13	158.577	39.075	37.252	2.088	.055	8.699
14	160.554	39.067	37.386	2.385	.081	7.289
15	162.142	39.056	37.314	2.430	.063	8.434
16	162.638	39.067	37.180	2.298	.067	8.485
17	162.978	39.087	36.524	1.757	.053	11.636
18	162.800	39.102	37.386	2.686	.073	7.989
19	162.531	39.111	37.233	2.483	.051	10.092
20	162.361	39.094	36.730	1.998	.059	10.088
21	161.605	39.038	37.121	2.516	.067	8.525
22	160.657	38.985	36.905	2.353	.055	9.808
23	158.347	38.889	36.953	2.579	.050	9.969
24	158.000	38.895	37.107	2.797	.048	9.948
25	156.426	38.921	36.754	2.320	.057	9.341
26	154.687	38.948	36.936	2.505	.052	9.465
27	150.794	39.000	37.009	2.524	.056	8.522
28	150.641	39.000	37.073	2.606	.055	8.513
29	148.529	38.958	36.751	2.264	.049	9.504
30	146.512	38.921	36.917	2.475	.051	8.695
31	141.456	38.833	36.951	2.573	.051	7.929
32	139.556	38.833	36.989	2.597	.050	7.812
33	137.640	38.833	37.066	2.677	.043	8.255
34	134.225	38.833	37.104	2.671	.042	8.027
35	132.040	38.833	37.065	2.569	.041	7.946
36	130.962	38.813	37.363	3.105	.037	7.873
37	128.213	38.758	36.824	2.271	.034	9.097
38	124.907	38.686	36.838	2.302	.038	7.714
39	124.109	38.667	36.930	2.431	.037	7.658
40	120.647	38.797	37.127	2.432	.039	6.813
41	119.035	38.785	36.794	1.998	.038	7.215
42	118.941	38.785	36.774	1.977	.038	7.209
43	118.086	38.775	36.731	1.921	.044	6.553
44	117.586	38.766	36.842	2.024	.050	5.958
45	117.479	38.760	36.376	1.629	.046	6.784
46	117.544	38.754	36.372	1.628	.046	6.794
47	117.775	38.748	36.503	1.729	.032	8.854
48	118.464	38.739	36.554	1.787	.030	9.571
49	120.783	38.723	36.539	1.830	.031	9.827

significant correlation. The t-values for this correlation are shown in Table V.

TABLE V

CORRELATION OF EQUIVALENT THERMAL MODEL VARIABLES TO THERMAL POWER TRANSFER/AREA

	t-Value		t-Value
Rectal Temperature (TG)	9.11**	Body-Hair Transfer Coefficient (KH)	9.08**
Average Body Temperature (TAVE)	3.57**	Surface Transfer Coefficient (H)	4.81**
Body Transfer Coefficient (K)	2.72**	**With 1% confidence level	

Computation of Control Signals

The next step in the development of the thermal model was the determination of a temperature that could be used as a forcing function for the heat transfer coefficients. Two temperatures were considered, the rectal temperature as measured or the average body temperature as computed from the same program that calculated body composition and temperature distribution. Physiologically, the thermal sensing center of the hypothalamus may be measuring a blood temperature that represents a weighted average of the blood from all parts of the body. Therefore, heat transfer mechanisms may be responding to an average body temperature. This average may be weighted by the volume of blood going to each individual component of the body. For example, the bones receive less blood than the gastrointestinal tract. The temperature of the skeleton probably contributes less to the temperature sensed by the hypothalamus than the gastrointestinal tract temperature. A correlation analysis was made of the two proposed temperature signals and the controlled heat transfer coefficients. The t-values for this correlation are shown in Table VI. They indicate that the average body temperature was significantly correlated to both the body heat transfer coefficient and the hair heat transfer coefficient. Neither of the two temperatures sources were highly correlated to the surface heat transfer coefficient.

TABLE VI

CORRELATION BETWEEN BODY TEMPERATURES AND THE CONTROLLED HEAT TRANSFER COEFFICIENTS

CONTROLLED VARIABLES	CONTROL SIGNAL RECTAL TEMPERATURE	 AVERAGE TEMPERATURE
	t-Value	t-Value
K (Body)	-.91	2.12*
KH (Hair)	5.85**	2.83*
H (Surface)	1.70	-.92
* - 5%) ** - 1%) Confidence level		

The procedures used to calculate the average body temperature and the surface heat transfer coefficient resulted in an interrelationship between these two values that was contradictory. Skin and hair temperatures lower than the average data caused the calculation routine to produce a higher heat transfer coefficient while, at the same time, caused the average body temperature to be computed slightly lower. This effect resulted in the poor correlation between the average body temperature and the surface heat transfer coefficient. Because the average body temperature was significantly correlated to two out of three of the controlled variables and its lack of correlation with the third controlled variable could be explained, and because the average body temperature appeared to be more physiologically acceptable, it was chosen as a forcing function for the thermal model.

Because of the poor correlation between the average body temperature and the surface heat transfer coefficient, the equation between the average body temperature and the thermal power transfer/unit area

$$\text{TAVE} = 35.9011 + 0.00764 * (\text{Heat/Area})$$

and the equation for the surface heat transfer coefficient as a function of thermal power transfer/unit area

$$H = 2.58215 + 0.04015 * (\text{Heat/Area})$$

were combined mathematically to produce an equation relating the surface transfer coefficient to the average body temperature

$$H = 2.25215 + 5.255 * \text{TAVE}$$

Because of the significantly high correlation of the thermal power transfer per unit area to all of the model variables it was decided to use the same procedure to develop equations relating the body heat transfer coefficient and the hair heat transfer coefficient to the average body temperature.

After establishing the relationships between the body, hair and surface transfer coefficients and the average body temperature, a CSMP implementation of the thermal cylinder model was used to dynamically solve for the steady state of the temperatures of each body component at selected weights. Respiratory vapor loss and skin vapor loss were defined by polynomial curves fitting the reported data. The total thermal power dissipated by the equivalent cylinder was computed from the polynomial equation that defined the metabolic rate as a function of weight. The CSMP simulation of the thermal model was run until steady state conditions were reached at each of fifteen selected weights. The resulting skin, hair and rectal temperatures appeared to be within the range of the reported data.

Respiration Modeling

To be able to model the heat loss due to respiratory vaporization, it was first necessary to establish a respiration rate of the model. The approach was to use a base respiratory rate, defined as a function of body weight in a thermoneutral environment, and a ventilation ratio determined by average body temperature.

The data by Kibler, 1959, indicated that the Brahman animals appeared to be closer to their physiological neutral temperature than either of the other two breeds. Using the data for the Brahman animals in the 50 F environment, a polynomial equation to define the ventilation rate, in liters per minute, as a function of animal weight was developed. This equation was then adjusted to define the ventilation rate of the Brahman animals having a rectal temperature of 38.65 C. This empirically determined equation for pulmonary ventilation rate thus defined the base ventilation rate at any given weight. The increase in ventilation rate caused by an increase in body temperature was represented by an increased ventilation ratio which multiplied the base ventilation rate.

The empirical equation for the base ventilation rate was developed using a rectal temperature as the base temperature. The ventilation ratio was also related to the rectal temperature. However, the model of the equivalent thermal cylinder used the average body temperature, not the rectal temperature, as the temperature signal for control. It was necessary to adjust the empirical ventilation rate equation and the ventilation ratio function to the average body temperature. Figure 24 is a plot of the average body temperature obtained from simulation runs of the equivalent thermal model versus the rectal temperature of the model. The data points were plotted from the steady-state solutions as the thermal model increased in size.

It is evident, in Figure 24, that there is not a linear relationship between the average body temperature and the rectal temperature of the model. The highest body and rectal temperatures occurred in the thermal model during steady-state solution of temperatures for an animal at 225 kg. The data points from that weight upward described a line which was slightly lower than the line of data points from the animals at weights up to 225 kg. Because most simulations of the model would be in the range of 225 kg upward, the relationship between the average body temperature and the rectal temperature was calculated from a line drawn through the data points for animal weights above 225 kg. Using this relationship between the average body temperature and the rectal temperature, the empirical equations for the ventilation rate and the ventilation ratio were adjusted to be functions of the average body temperature instead of the rectal temperature.

The average value of moisture pickup per liter of ventilation air, reported by Kibler, 1959, was used with the ventilation rate to predict the vapor transfer from respiration. The thermal power transferred by ventilation was calculated as the power to convert the vapor from liquid to gas molecules.

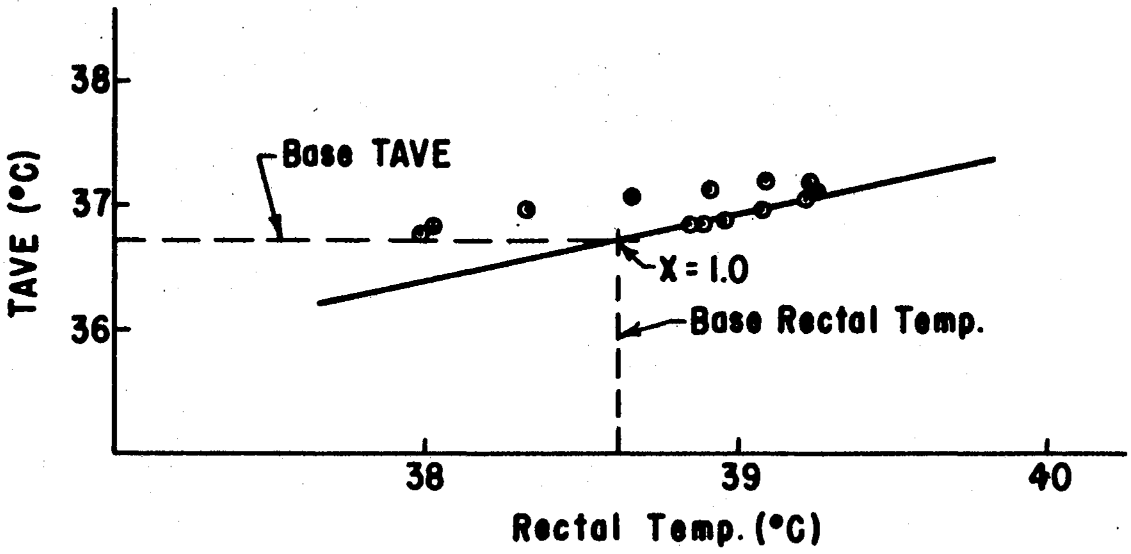


Figure 24. Average body temperature computed during simulations compared to rectal temperatures.

Ratiation Heat Transfer

Although preliminary simulations using the surface heat transfer coefficient as computed appeared to simulate skin and hair temperatures adequately, there was no distinction between the heat transfer by radiation or by convection to the air. The radiation portion of the heat transfer had to be determined. Also future simulations would require a separation of radiation and convection heat transfer, to allow utilization of the surface convective heat transfer coefficient as a predictor of the moisture transfer.

The calves, in the Missouri study, were stanchioned side by side within pens having aluminum walls. This configuration eliminated the possibility of calculating the radiation heat transfer by assuming that the animals were radiating into a black body that absorbed all of the theoretical radiation heat transfer at the temperatures reported. The animals were not radiating into a true black body. They were either radiating into an aluminum side-wall or another animal at the same body temperature. The radiation heat transfer had to be calculated from the theoretical formulas of heat transfer between grey bodies. These calculations were straight forward applications of the radiation formulas and view factor configuration charts contained in Parker, Boggs, and Blick, 1969. The pen configuration and a summary of the calculations are included in Appendix E. Instead of the 59.8 $Kcal/M^2$ estimated by the theoretical black body formulas, the animals were radiating approximately 41.9 $Kcal/M^2$. The calculated radiation was therefore approximately 70% of the radiation predicted by the theoretical black body heat transfer equations.

The constant value of 41.88 $Kcal/M^2$ of radiation was subtracted from the value for combined heat transfer. The values used for the combined heat transfer were taken from the simulations for steady state temperatures of the equivalent thermal model. These values made possible a rapid recalculation of the new convective heat transfer coefficient as a function of the average body temperature. During subsequent simulations the new convective heat transfer coefficient was used. The radiation heat transfer was calculated by assuming that the animals were radiating into a black body but that only 70% of their surface was radiating. This simulation procedure eliminated complicated formulations of environment conditions which would have applied only to this particular set of data.

Skin Vaporization

Heat transfer and moisture transfer coefficients are theoretically related by the formula reported in the review of literature. Solution of that formula for the conditions during the Missouri study resulted in the relationship that;

$$HM = 4673\ H$$

where HM is the mass transfer coefficient in grams per meter squared per hour. This mass transfer coefficient multiplied by the differential in the humidity ratio, between the assumed saturation humidity ratio of the body and the environment humidity ratio, predicted a larger moisture transfer value than was reported. The assumption that the humidity ratio of the skin should be near saturation has been debated by Esmay, 1969, who cited experimental evidence that skin vapor saturation does not exist.

Predictions of the humidity ratios at the skin appeared to be vague. Therefore, the possibility of using a model involving two resistances to represent moisture transfer, the convective resistance and the resistance of the animal's body, was considered. This possibility is illustrated below

Where Ws is the humidity ratio at saturation at body temperature, Wse is the humidity ratio at the skin surface, and We is the humidity ratio of the environment, RB is the resistance of the body to moisture transfer, RH is the resistance of the air to convective moisture transfer and M is the moisture transfer rate in grams per square meter per hour.

The equation for moisture transfer rate from the saturation humidity ratio to the environment humidity ratio is analogous to Ohm's law for current flow through two resistances;

$$Ws - We = \dot{M}\ (RB + RH)$$

From this equation it is possible to solve for the resistance of the body to moisture transfer as follows;

$$RB = \frac{(Ws - We)}{\dot{M}} - RH$$

The theoretical value for the convective moisture transfer coefficient, HM, was assumed to be correct. Also, the resistance, RB and RH, are equal to the reciprocal of the moisture transfer coefficients, HB and HM, which are conductance values. Using values for Ws and We from a psychometric chart, the resistance of the animal's body to moisture transfer was computed from the Missouri data for skin moisture transfer. This computation did not require the undefined humidity ratio at the skin surface.

Solutions for the resistance of the animal's body to moisture transfer were made at each of the weights used during previous simulations. At the environmental temperature, 50 F, the resistance of the body to moisture transfer was significantly larger than the resistance from skin surface to environment. This condition supports the conclusions of Pedersen, 1968. The reciprocal of the body resistance was calculated and correlated to the average body temperature. This correlation resulted in a prediction value for the body moisture transfer coefficient as a function of the average temperature of the body. Thus the body moisture transfer coefficient also was controlled by the average body temperature similar to the other heat transfer coefficients. The resulting equation for moisture transfer then became,

$$M = \frac{(Ws - We)\ HB\ \ HM}{(HB + HM)}$$

This equation combines control of the moisture transfer of the body with the effect of environmental humidity ratio. A high environmental humidity ratio will reduce moisture transfer from the equivalent thermal model. This implementation appears to be consistent with reality.

Environment Modeling

Brooker, 1966, reported equations that could be used on a computer to calculate a humidity ratio given the relative humidity of the air and the air temperature. Equations 4, 6, and 12 from Brooker were used directly to compute the humidity ratio of the environment and the saturation humidity ratio of the animal. In the model assembled, it was assumed that the humidity ratio of the air would not be a variable quantity. This assumption is correct for a short time period. Knowledge of the average humidity for several weeks makes it approximately correct over a longer time period.

Modeling of the environmental temperature and also the radiation temperatures seen by the animal was accomplished by using the CSMP SINE subroutine for four temperatures. The temperature of the environment, TE, was considered to be the air temperature surrounding the animal. The radiation temperature of the environment, TX, was considered to be the average temperature of the surrounding area as seen by the animal. If only one temperature was to be considered, TX was set equal to TE. Also the temperature of the sun and the temperature of the earth were made available to represent, respectively, sources of short wave radiation from the sun and sky and reflected long wave radiation from the surrounding earth.

The equations for grey body radiation from the animal to the three radiation temperatures were used to implement radiation transfer. For economy the radiation formulation was divided into three sections. The first section is calculated in the initial portion of the simulation and involves only the environment factors as defined by the user. The second section of radiation calculations are those constants involving the animal area. These computations were inserted into the section where the animals composition and area is updated periodically. The final computations involving the temperatures themselves are placed as required within the dynamic section of the model.

Thermal Simulations, Steady-State Results

The final model schematic diagrams for the thermal section and their listings for CSMP implementation are shown in Appendix F. Figure 51, Appendix F, is the master flow chart of the thermal model showing the main inputs and outputs of the thermal model blocks as well as the main interconnections.

During simulation runs to verify the thermal model, the empirical polynomial equation for heat production as a function of weight was used as an input. At thirteen different weights a dynamic solution of the thermal model was continued until steady-state conditions were reached. The temperatures from the steady-state solution of the thermal model were compared with the original Missouri data. This comparison for hair, skin and rectal temperature is shown in Figures 25 through 27.

A curve connecting the simulation steady-state solutions appears to fall within the data for the hair and the skin temperatures. The steady-state solutions for rectal temperatures at weights above 150 kg were very close to the reported values. Below 150 kg the steady-state solution of the equivalent thermal model resulted in a rectal temperature deviation as large as 1 C lower than the reported values. This deviation implied that either the computational routine to determine composition or the distribution of heat generation within the equivalent thermal cylinder was not entirely correct. These steady-state solutions indicated that the equivalent thermal model as developed would be acceptable as the first approximation of a thermal model because the practical use for the complete beef model would be for weights above 150 kg.

The steady-state solutions at thirteen different weights, from 60 kg to 375 kg also verify that the equivalent thermal model formulation produced a model which could simulate rectal and surface temperatures during the growth of an animal. This is the first known dynamic thermal model that simulates surface temperatures during the growth of

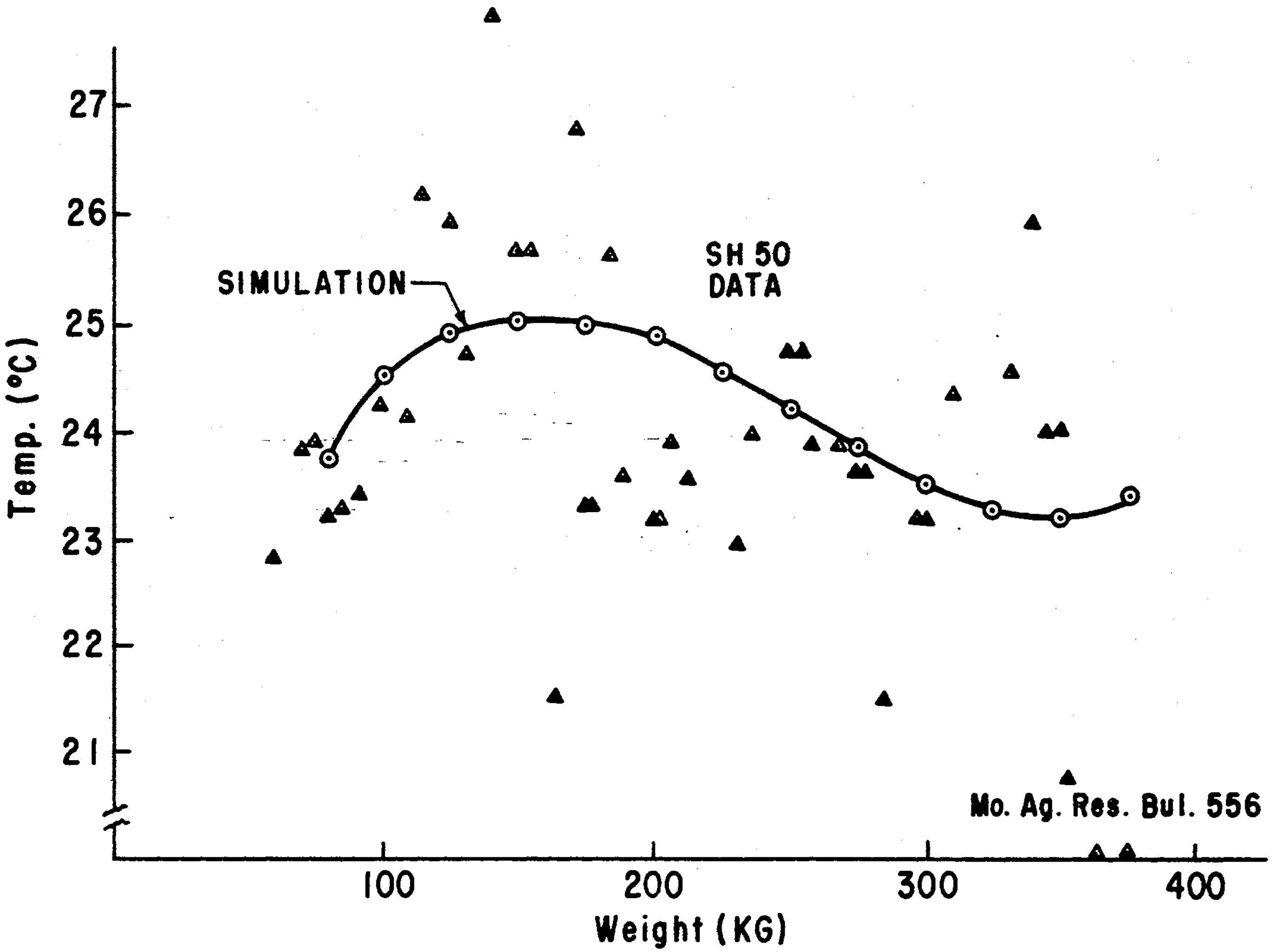


Figure 25. Results of steady-state solutions for hair temperatures compared to data.

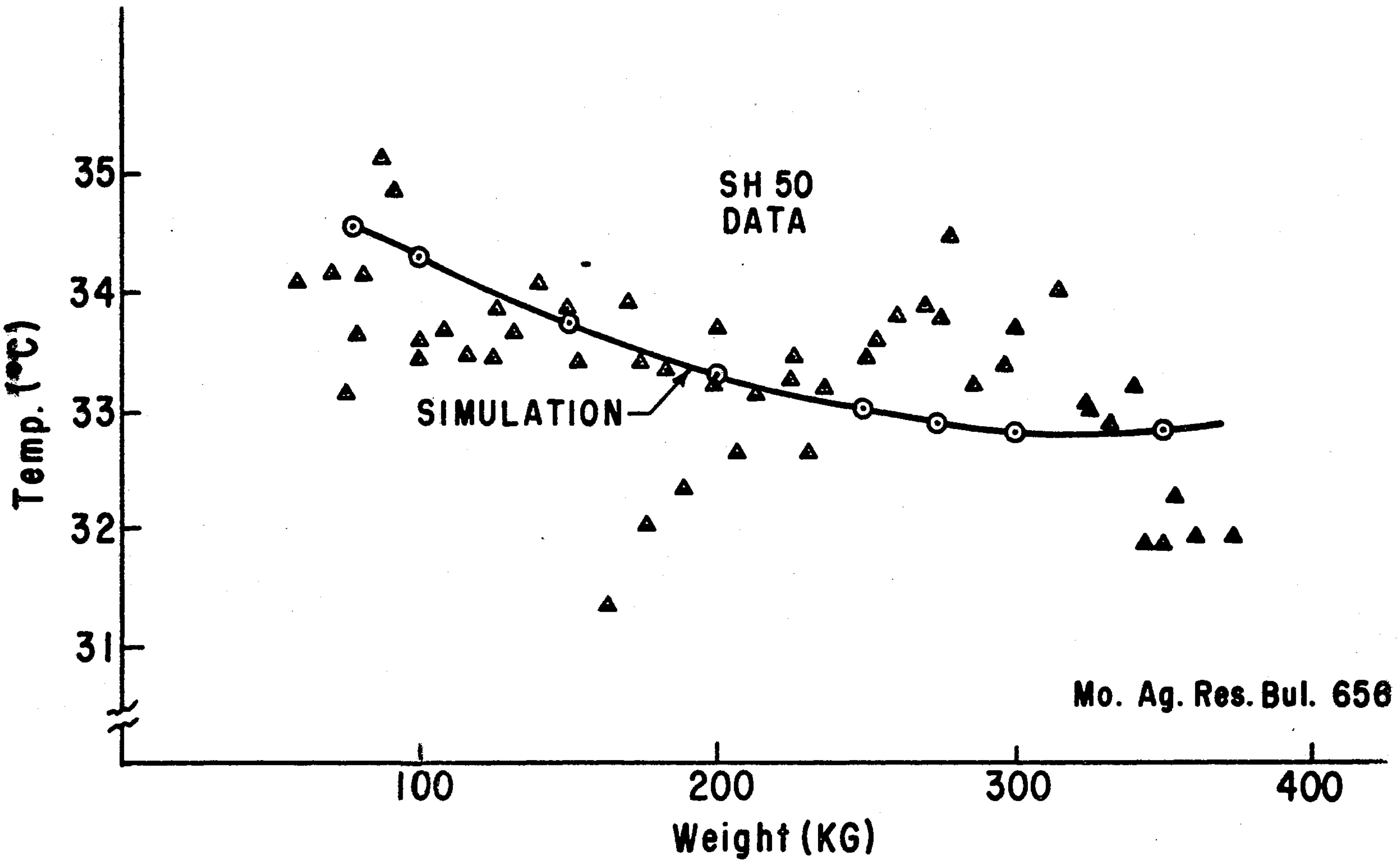


Figure 26. Results of steady-state solutions for skin temperature compared to data.

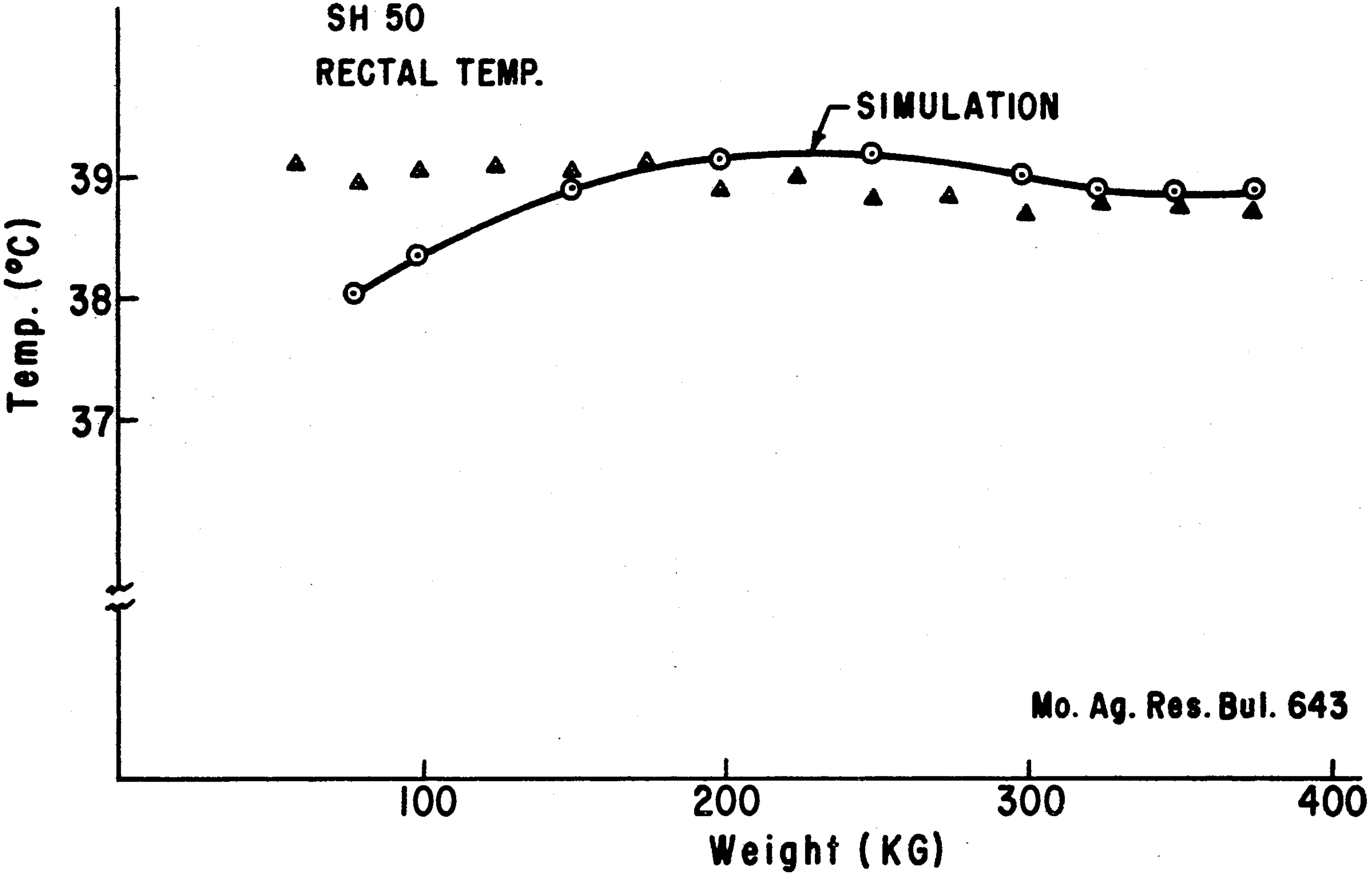


Figure 27. Results of steady-state solutions for rectal temperatures compared to data.

the animal. All other dynamic thermal models reported in the literature were restricted to one body weight.

Steady-state solutions of the thermal model for the respiratory evaporative heat loss as compared to the Missouri data is shown in Figure 28. The actual data points are not plotted but the data range is indicated. Kibler, 1959, originally fit the data with two exponential curves. This fit resulted in two curves that were not accurate where the data changed slope rapidly. This is also illustrated in Figure 28 by the line representing the reported exponential curves. The exponential curves passed through the low side of the data range at the inflection point in the data curve. The steady-state solutions predicted by the thermal model also falls within the data range. Therefore the mathematical modeling of the respiratory evaporative heat loss was considered acceptable.

A comparison of the steady-state solution of the thermal model for the skin evaporative heat loss and the original data is shown in Figure 29. There was no original data reported for weights below 175 kg. Above this weight, steady-state solutions and the reported data show an excellent correlation.

To compute the evaporative heat loss from the respiratory system and from the skin it was necessary to solve for the total vaporization. Total vaporization was also reported by Kibler, 1959. Comparison between the steady-state solution of the equivalent thermal model and the reported vaporization is shown in Figure 30. The steady-state solutions appear to be well within the data range reported.

To further verify that the equivalent thermal model was valid, it was used to simulate results obtained in other experiments. The

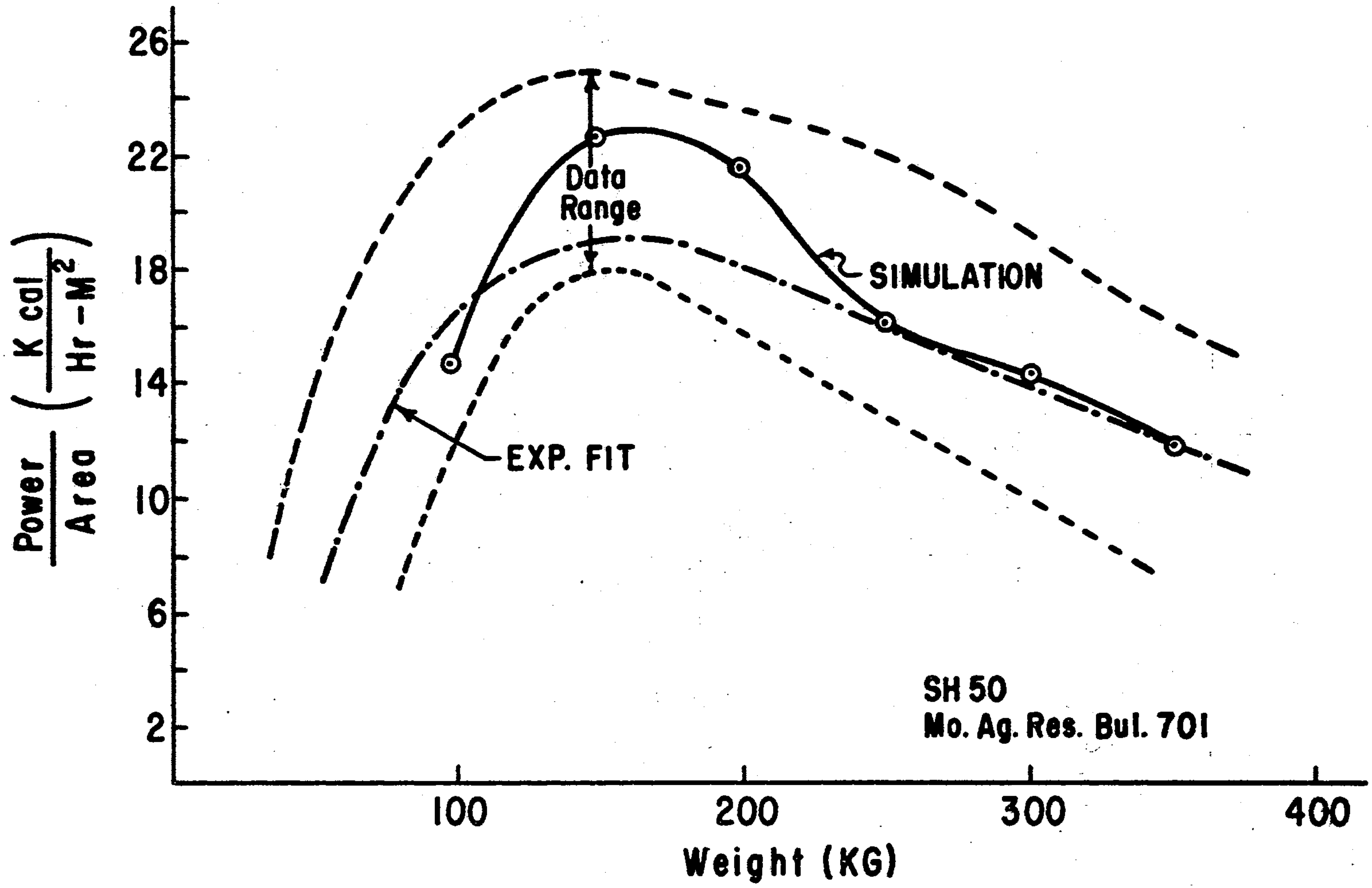


Figure 28. Steady-state solutions for respiratory heat transfer compared to data.

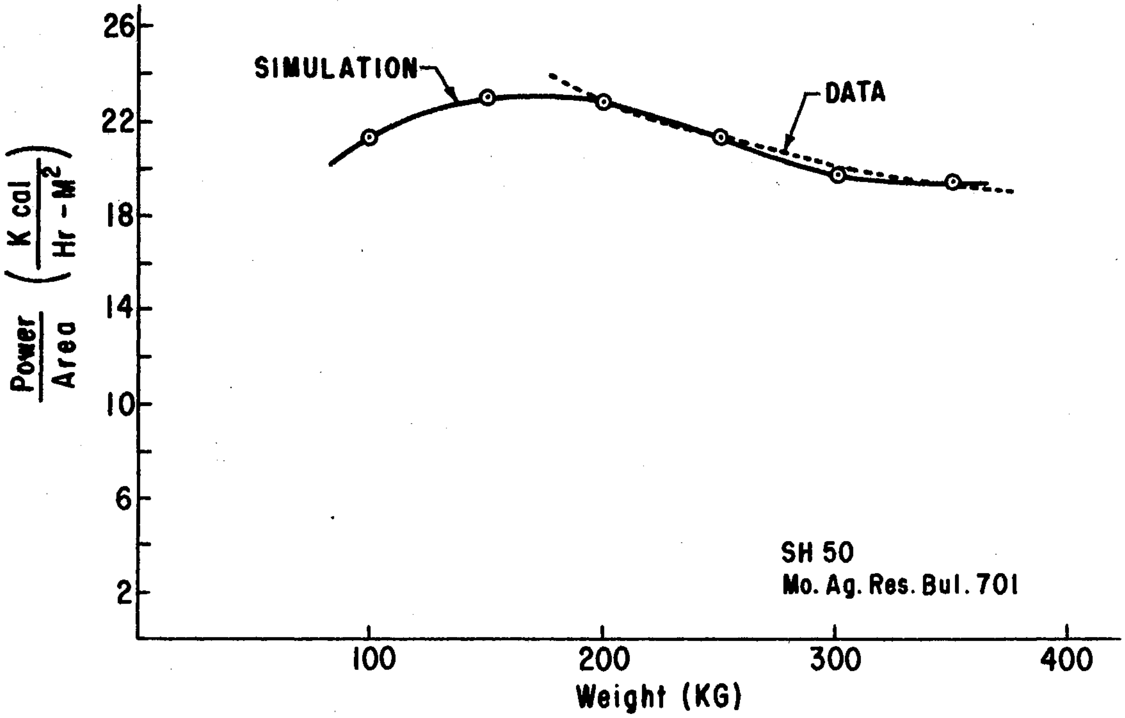


Figure 29. Steady-state solutions for skin evaporative heat transfer compared to data.

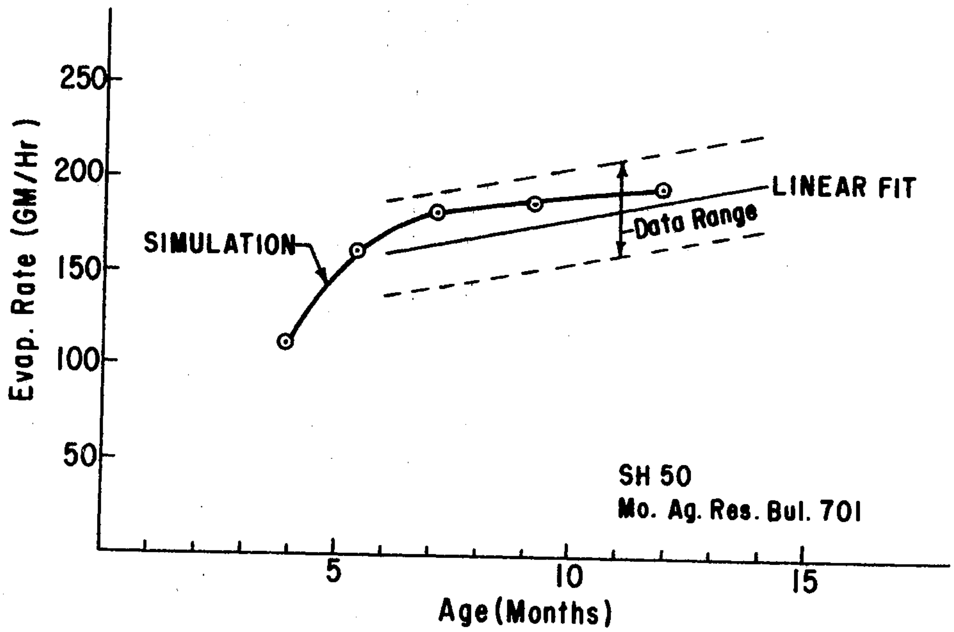


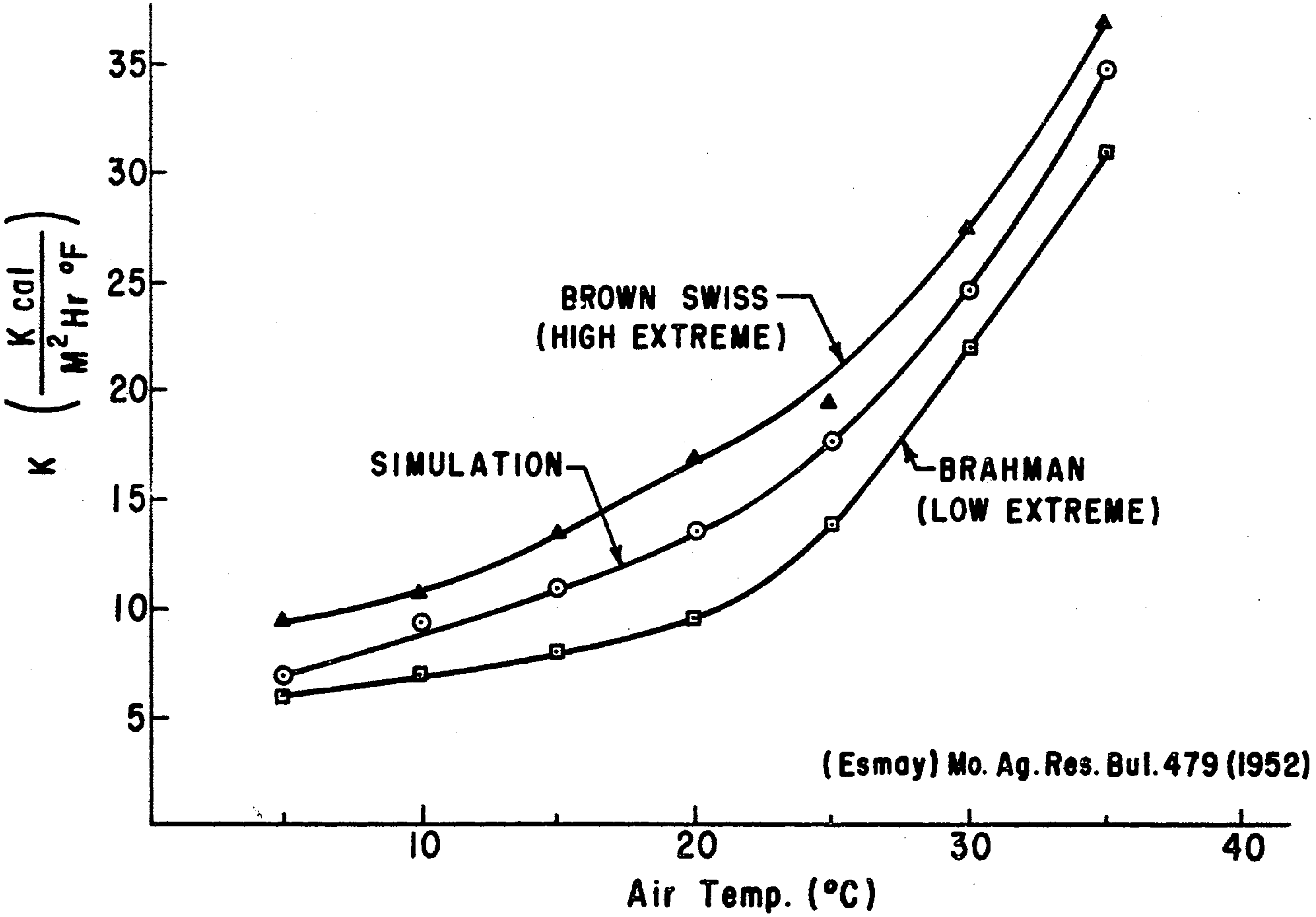
Figure 30. Steady-state solutions for total vaporization compared to data.

data from these experiments was not used in the development of the equivalent thermal model. This earlier research is shown by Esmay, 1969, as graphs of overall theoretical body heat transfer coefficients. Two curves from these graphs, a curve for the Brown Swiss which was the high extreme, and a curve for the Brahman which was the low extreme, are shown in Figure 31. Other breeds of dairy and beef animals produced curves that lay between these two extremes.

The equivalent thermal model at 375 kg was allowed to reach steady state solution for a series of environmental temperatures corresponding to those used in the reported experiments. The resulting curve connecting these steady-state solutions falls between the two extremes shown in Figure 31. This verification was done without any manipulation of the parameters of the existing thermal model that had been used to obtain the steady-state solutions for comparison against the original calibration data. Thus, the response of the equivalent thermal model to a different set of thermal conditions verified that the modeling concept of the equivalent thermal cylinder was acceptable.

Thermal Simulations, Dynamic Results

The ultimate use of a dynamic mathematical model is for dynamic simulation. However, data showing dynamic responses of beef animals to either step-changes or cyclic thermal changes were extremely limited. The dynamic response of a human being to a 7 C step-change, reported by Crosbie, Hardy and Fessenden, 1961, was selected as the best available dynamic indication of the thermal model performance. Results of dynamic simulations of the performance of the equivalent thermal model for beef animals are shown in Figure 32. Unlike the



(Esmay) Mo. Ag. Res. Bul. 479 (1952)

Figure 31. Comparison of the overall "K" value predicted by simulation to data not used in development of the model.

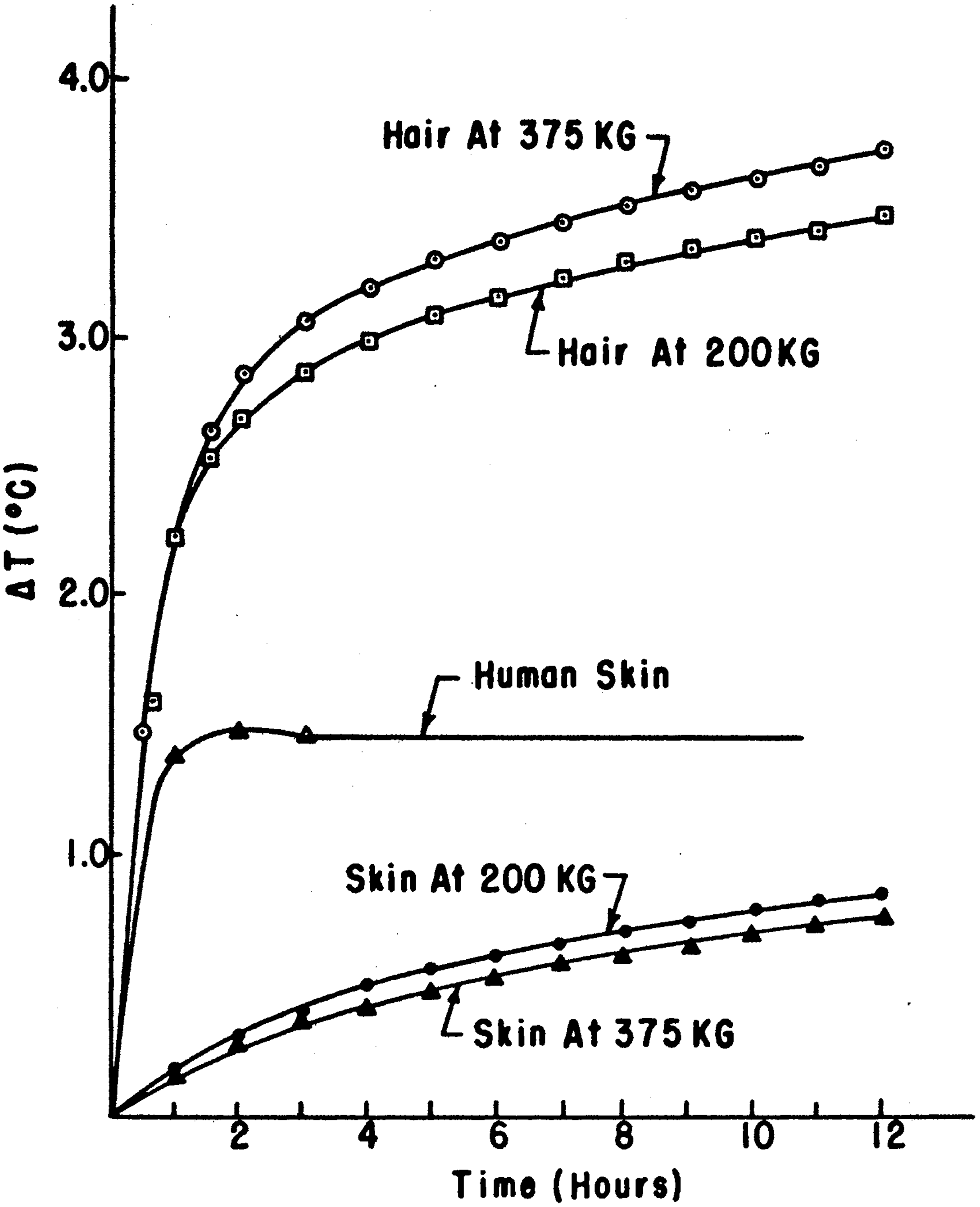


Figure 32. Simulated dynamic response of beef hair and skin temperatures to a 7 C step change in the environment.

human being, the insulating hair coat of beef animals provides a moderating effect for the skin temperature. The hair temperature responded more rapidly and the skin temperature of the beef animal responded less rapidly than the human skin response to a step change. The skin temperature of the smaller simulated beef animals, 200 kg, showed a faster dynamic response than the larger, 375 kg, simulated beef animal. Considering the difference between humans and beef animals, especially the insulating hair coat, these dynamic responses appeared to be appropriate.

Another verification of the thermal model came when the thermal section was added to the complete model. Then the average temperature of the simulated beef body was used as a signal for the eating control. The energy required for growth was computed by using the growth section developed by Witz. The energy density forcing function for the growth section was set to achieve the growth reported. The energy required for growth was subtracted from the energy of the food eaten. The remaining energy of the food was converted into thermal energy. The eating control system was adjusted so that the simulated animal would attempt to maintain a set body temperature. With this configuration, the amount of energy eaten during simulation represented both the growth energy and the thermal energy required to maintain the equivalent thermal cylinder at the set point temperature.

Thus, the energy input to the thermal cylinder became a controlled function of the body temperature. This configuration was the first use of the thermal section and the growth section together. Nevertheless, during simulations the model decided to eat approximately the correct amount of grain and forage. During these simulations a method for eating two different rations was developed. The amount of grain fed to the model was arbitrarily set at six pounds per day as was done in the original research work. The model usually came within 15% of the required amount of forage. The equivalent thermal model responded dynamically to eat twice a day. These results meant that the equivalent thermal model was valid. It predicted the gross energy required to maintain body temperature and it dynamically responded with acceptable correlation to biological eating activity.

Composition Recomputed

During attempts to incorporate the growth section, developed by Witz and the thermal section into the same model, a discrepancy in the composition of the animals was noted. Figure 33 illustrates this discrepancy. Witz, by doing extensive library research, had selected several sets of data showing the composition of beef animals divided into meat, skeleton and fat. Also, because his study was orientated toward feedlot production and marketing, he used the dressing percentage to establish data for the offal. The offal was considered the portion of the animal not included in the carcass weight. This portion includes skin, feet, head and tail which are not part of the gastrointestinal tract.

This definition of offal differed from that used during the development of the thermal cylinder where only the weight of the gastrointestinal tract was considered. The result was that the composition used to calibrate the thermal model had the meat tissue and offal curves reversed in magnitude when compared to reported data. Also, the values of skeleton and fat used in the thermal composition

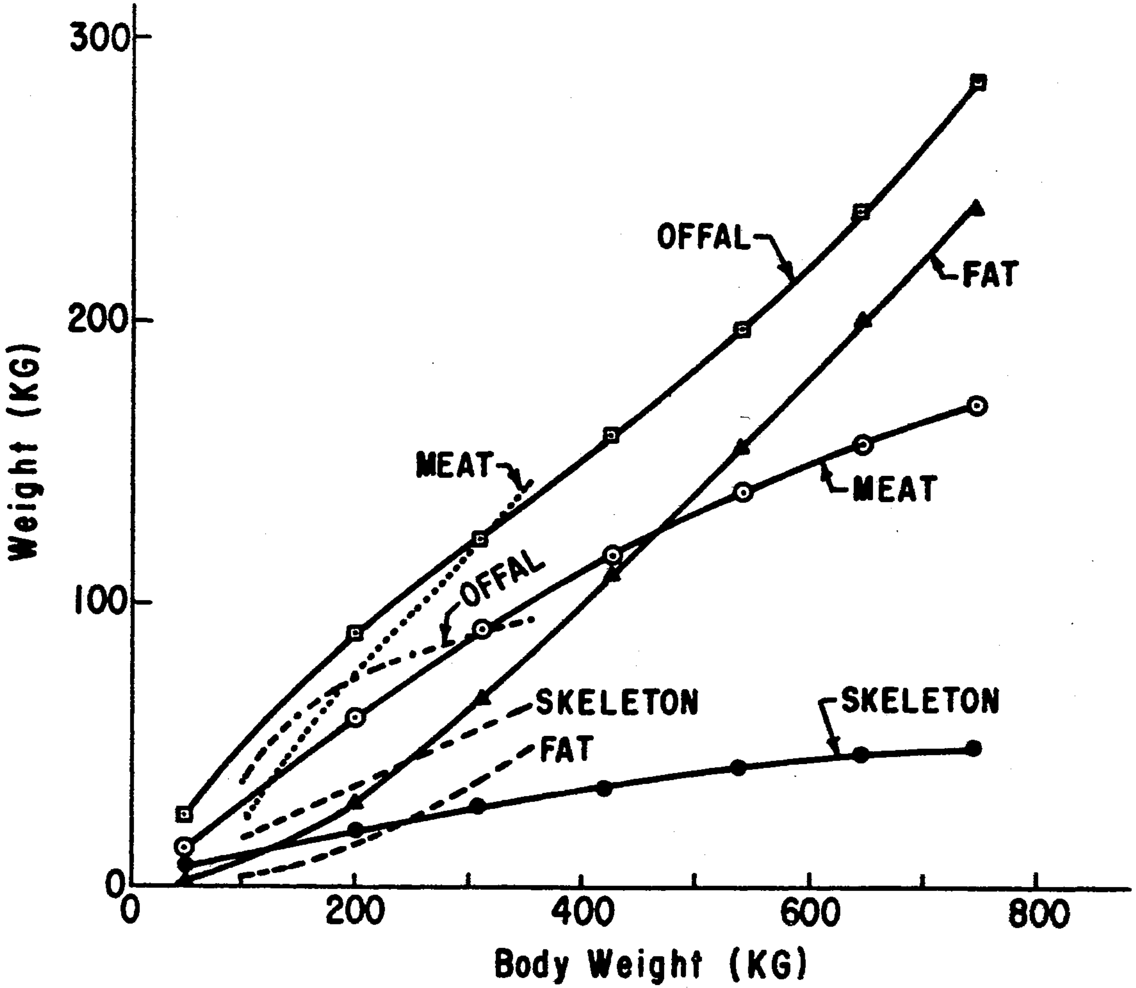


Figure 33. Comparison of thermal cylinder composition to body composition predicted by the growth section. The thermal cylinder composition is represented by dashed lines.

were respectively higher and lower than the data collected by Witz. This discrepancy occurred because the percentages used in the estimation of fat and skeleton came from data using carcass weight instead of live weight.

Because of this discrepancy, the composition of the equivalent thermal model was recomputed and new solutions for the body heat transfer coefficient and for the average body temperature were made. The results indicated that the body heat transfer coefficient was increased very slightly and that a new average body temperature was required as a forcing function. There was a linear relationship between the old and new heat transfer coefficients and the old and new average body temperature. By using these relationships the equations developed as a function of the old body temperature could be transformed into equations to be used with the new body temperature associated with the correct composition of the body. This was accomplished and was verified by re-running the simulations. The result was nearly identical to solutions achieved using the old compositions and the old body temperature.

Thermal Control

After the growth and thermal sections were combined and development began on the chemical section it became apparent that the average body temperature was not an appropriate control signal for the eating function. Simulation runs in the higher temperature, 80 F, environment using the average body temperature as the control signal did not correspond correctly to the data. The simulation runs indicated that the rectal temperature actually dropped while the data showed an increase.

Upon reviewing the literature on thermal regulations, especially the thyroid control system presented by Distefano and Stear, 1969, and the thyroid reactions of the beef cattle in the Missouri study as reported by Blincoe, 1958, a hypothesis was made that a basic metabolic rate per unit volume of flesh existed. Under high temperature environmental conditions the metabolic rate per unit volume decreases to this basic rate or minimum metabolic rate, and does not go any lower. This rate was assumed to have been established through hereditary development.

When the environment temperatures are reduced, or when the animal is smaller, it was assumed that the thyroid gland would increase the metabolic rate as necessary to maintain the set body temperature. The precision of body temperature control implied that a proportional plus integral controller must be the control mode for the body set point temperature. Upon close examination, the thyroid model proposed by Distefano and Stear, 1969, could be considered an integral control system. The combined reaction of the thyroid gland, the pituitary gland, and the thyroid protein binding factor can be interpreted to represent a biological integrator. The protein binding factor increases in response to the thyroxine concentration in the blood and thus readjusts the set point which is then maintained by interaction between the pituitary and thyroid gland. This is analogous to an integrator readjusting a control set point in a reset controller.

The hypothalamus provides the error signal that is a forcing function for the pituitary and thyroid gland integrator section. The thermal state of the body is usually accepted as being the feedback signal to the hypothalamus.

Based upon these assumptions and hypotheses, a basal metabolic rate controller was modeled as shown in Figure 56, Appendix F. The CSMP listings necessary to implement this model are shown in Appendix F. The total power committed to the basic metabolic rate is calculated from a parameter defining the basic metabolic rate per unit volume and the weight of metabolic active tissue as calculated in the composition routine. This total power, PBMR, represents the basic metabolic power that must be lost by the animal irregardless of the environmental conditions.

When environmental conditions, or animal size, require a slightly higher basal metabolic rate, the temperature error signal adjusts the integrator controller whose output, VTBMRZ, is used to increase the basic metabolic rate as required. An inclusive or logic module is used in the feedback to the integral controller to enable the controller to be turned on when environmental conditions require and to remain active until environmental conditions reach a state where the basic metabolic rate is sufficient to maintain body temperature.

Use of this basal metabolic rate controller resulted in the beef model reacting according to experimental data on metabolic rates in high and low temperature environments. For this reason, as well as for the physiological simularity to the pituitary-thyroid gland system, this control implementation was considered to be valid.

Theoretically, a smaller animal, enclosing proportionately less metabolizable tissue per unit of skin area should have a higher basal metabolic rate at the same environment than a larger animal. Experimental data confirms this expectation. The results obtained using the basal metabolism controller should have also verified this relationship. However simulations involving beef models of various weights, indicated that the relationship in the model was reversed. The complete model required higher basic metabolic rates per unit volume in the larger animal than it did in the smaller animals.

These results were interpreted to mean that the original assumption of heat generation rates within the various tissues were not correct. The output of the basal metabolic rate controller VTBMRZ, thus became an analytical measurement that was not available before this model development. However, because the controller also set the correct basal metabolic rate, and because other sections of the beef model needed further development work, investigation of the correct distribution of the heat generation rates within the body components was not completed.

A brief investigation using a least squares minimization technique to establish the correct heat generation rate of offal, meat, fat, and skeleton indicated that the offal should have a heat generation rate of approximately 3 to 3.5 times the tissue heat generation rate. The heat generation rate distribution made in the original development had one heat generation unit in the offal to one heat generation unit in the meat. The same investigation showed that zero heat generation rates could be assumed for fat tissue and a very minimal rate assumed for skeleton. The results of this brief investigation were not verified.

CHAPTER VI

DIGESTIVE SECTION

Eating Control

The analog circuit of Kleiber's model included a comparator logic module as the eating control. This logic module was retained throughout model development. At various times the forcing function was changed from a temperature signal to a chemical signal but the principle remained the same. Eating started when the control signal went below a set point and stopped when the signal was above the set point.

The method of eating control is illustrated in Figure 34. Whenever the chemical energy control signal, VBLD, fell below the control set point, VACMIN, the model began to eat either grain or forage. Eating continued until the control signal again passed above the set point level, then the model inspiration signal, ISPR, would be set to zero and the model would cease eating. This state would continue until the control signal again passed below the set point.

The Shorthorn animals in the Missouri research were fed a combination of grain and hay that resulted in a minimum value for TDN of 0.58. This minimum value occurred at maximum hay intake. Higher values of average TDN, up to 0.67, were maintained throughout the experiment because the grain/forage ratio was higher than the grain/forage ratio at maximum hay intake. Montgomery and Baumgardt, 1965, concluded that feed with TDN higher than 0.57 was eaten with the animal using an eating control mode other than rumen volume. Because of this conclusion and because feedlot beef cattle will always receive high energy feed, the rumen volume control mode for feed intake was not implemented.

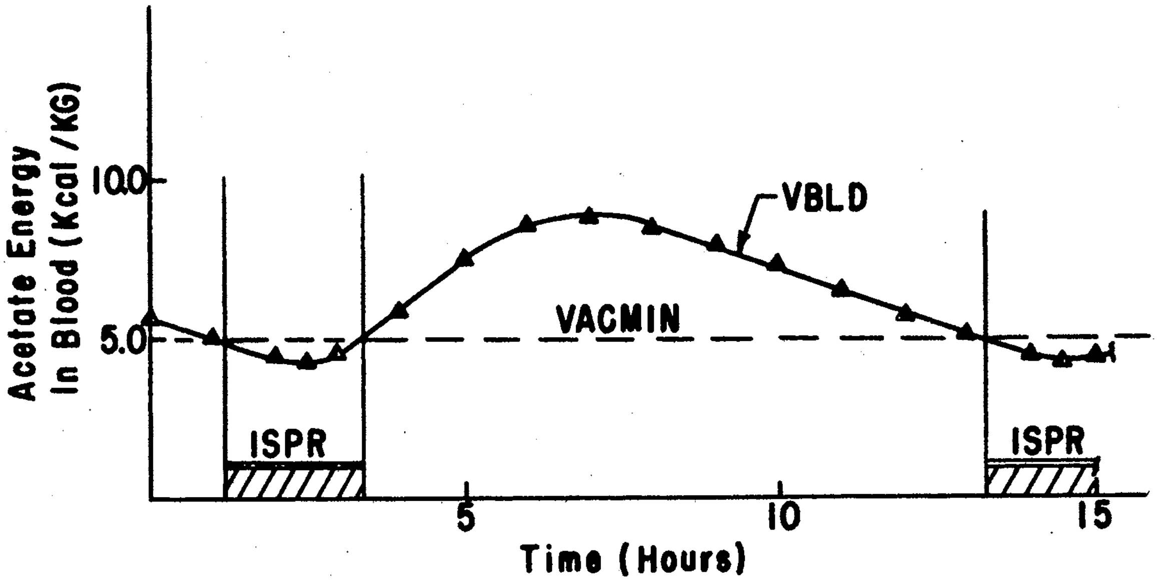


Figure 34. Plot of blood acetate energy concentration, VBLD, as a function of time, showing the eating periods when VBLD is below 5.0.

During testing of the model against the Missouri data, a limitation of the grain ration and ad lib consumption of the forage ration was required because the animals in the Missouri research were limited to six pounds of grain per day. A food mode module with the option of setting the grain level at a desired weight was developed. A FORTRAN routine was used in the logic module to update at feeding time the total grain consumption allowed. Thus, the model was limited to a desired grain level per feeding. When the desired grain level was reached during a particular feeding period, the logic module would switch rations and the model would complete the necessary intake of energy by consuming forage. When the control signal indicated sufficient energy intake the model ceased eating.

The eating rate was originally defined as a constant. However the eating rate is a function of mouth and throat size which is related to body weight. So, in later versions of the beef model, the eating rate of grain was made a function of body weight. The eating rate for forage was then assumed to be a linear function of the eating rate for grain. An extensive library search was made but no definite reports of eating rates as a function of weight or age were found. Therefore, arbitrary parameters which appeared to fit the model were selected. The solution for better parameters was made during the optimization of the complete model.

When food enters the rumen, there is a time delay until that food can be digested by the microorganisms and made available for absorption through the rumen wall as acetate, propionate or other higher carbon molecules. The data reported by Simkins, Suttle and Baumgardt, 1965, showed the response of the volatile fatty acids, acetic and propionic, in the blood of dairy animals. The response curve of acetate concentration in the blood during the eating portion of the experiment was similar to the response of a system having a first order lag and following a ramp forcing function.

The animals in the study were assumed to have eaten at a uniform rate, simulating a ramp forcing function. A digestive lag time was calculated from the response curve of the acetate concentration in the blood by the expedient method of plotting the acetate concentration curve as a function of time. The eating function was assumed parallel to the latter portion of the acetate concentration curve. Then the lag time was measured between the value of the eating function starting at zero and the reported data for acetate concentration. This procedure is illustrated in the Figure 35. Only two sets of data were studied, with the estimated digestive lag to be between 0.8 to 1.6 hours. The average value of 1.2 hours was selected. Its choice reduced the possibility of future instability during simulation runs.

A module to implement digestive lag was inserted between the state variables for grain and forage weights in the rumen, QVG and QVF, and the chemical section. The outputs from the integrators representing the first order lag, QFAG and QFAF, represented the quantity of grain and forage available for fatty acid production. This configuration resulted in a delay time between intake of food and its availability for use by the animal.

During the earlier model development the digestive lag was not changed when eating stopped. When the model stopped eating, an abnormal situation developed. The quantity of grain or forage available for fatty acid production slightly exceeded the quantity of grain or forage that was in the rumen. The error was relatively minor and, therefore, not corrected until the assembly of the final model.
At that time, a small logic module in FORTRAN was added to remove the digestive lag from the circuit when the animal was not eating and the quantity of food available for fatty acid production equalled the quantity of food in the rumen.

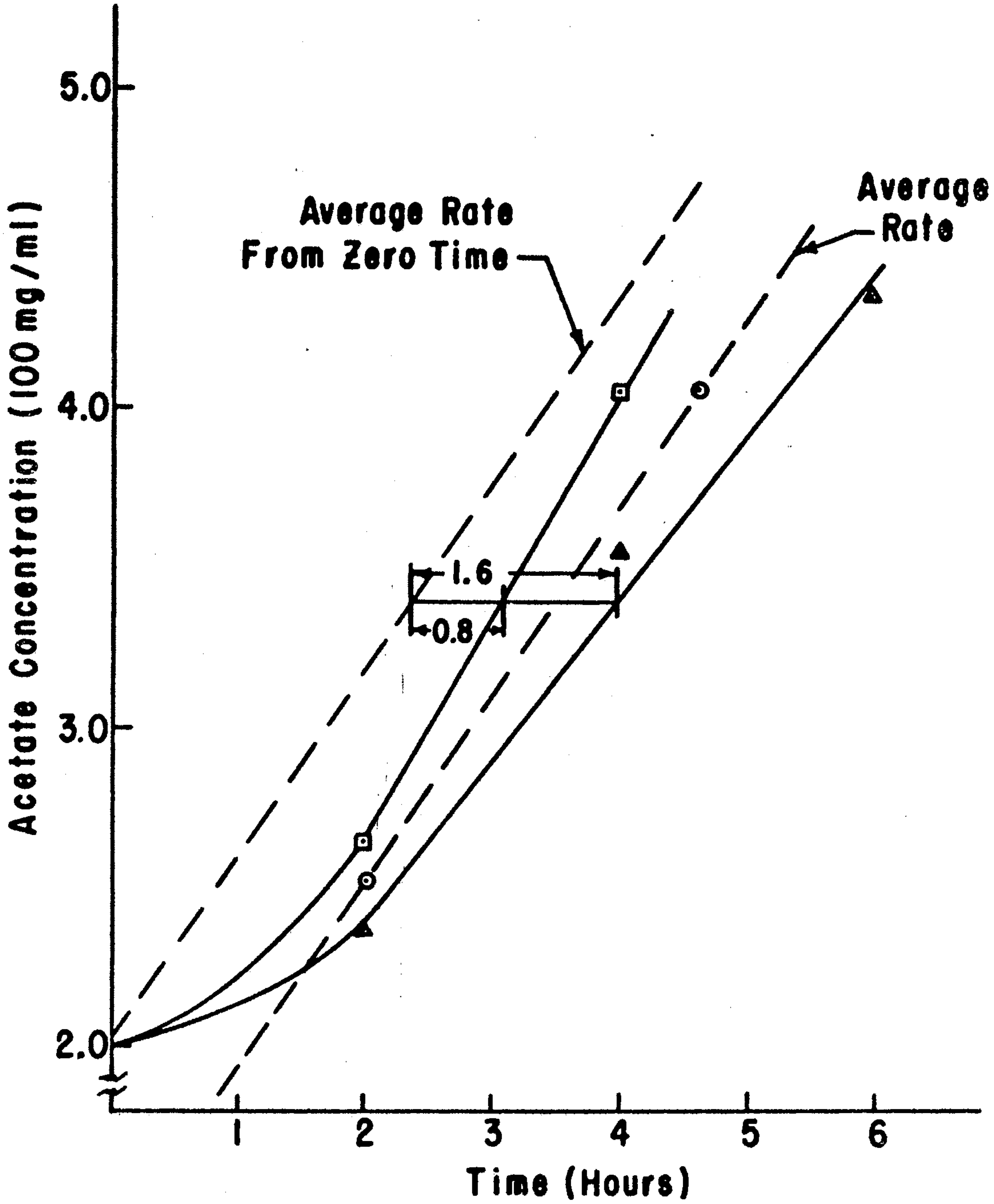


Figure 35. Illustration of the solution procedure to determine the digestive lag from two sets of data showing dynamic response of acetic acid concentrations in blood.

The absorption rate of the fatty acids from grain and forage was a quantity that could be calculated after a few simple assumptions were made. The main assumption was that the rumen and the intestines acted similar to a capacitor which stores energy and then dissipates it through a fixed resistance. In electrical analogy, the current is a function of the energy contained in the capacitor and a constant parameter defined by the resistance and capacitance of the circuit. In the beef animal, the flow of energy from grain and forage through the rumen walls was assumed to be similar to electrical current, and therefore to be a function of the food contained in the rumen multiplied by a conductance rate. Physiologically, at a given body size, this assumption is rational because all of the food must pass through a given area of rumen and intestine wall. The food absorbed must pass through a constant resistance. The reciprocal of this resistance is the conductance parameter, called absorption parameter hereafter.

As the animal grows, the amount of conducting area within the intestines and rumen would logically increase. However, no data were located which would allow a reasonable estimation of this increase. Furthermore, passage time of grain and hay through bovines, as reported by various authors, especially Blaxter, 1962, did not reveal the rate of passage as a function of age. Lacking evidence that there was a variation in the absorption parameter as a function of size or weight, a constant value was assumed to be approximately correct for the animals that might be simulated with the model.

To calculate an absorption parameter for food passing through the rumen and intestine walls, an estimate was made, based on Blaxter, 1962, that approximately 72 hours was required for passage of grain and approximately 120 hours was required for the passage of forage through the digestive system. Selecting any set of values for grain and hay consumed per day from the Missouri data, the total contents of the food retained in the rumen and intestines could be calculated. The reported values of total digestible nutrients for grain and hay were then used to calculate the theoretical weight of the digestible carbohydrates in the rumen and intestines. The answer was the average value of digestible food contained in the digestive system. The instantaneous value of digestible food was this average value plus or minus one-half of the digestible food consumed per feeding.

By dividing the average amount of digestible food eaten per feeding by the time between feeding periods, the absorption rate of food nutrients through the rumen walls was calculated. Finally, the absorption parameter was calculated by dividing the absorption rate by the average quantity of food available in the rumen.

If the passage time remains the same despite the size of the animal and if food absorption is a linear function of the quantity of food in the rumen the absorption parameter is a constant. There is a constant relationship between the weight of food in the rumen and the quantity consumed at each feeding. Therefore, any one set of feed data can be used to calculate the absorption parameter. An example of the calculations is given immediately below.

Assume for grain:

Eaten/Day = 2.68 kg/day = 1.34 kg/feeding

Passage Time = 72 hours = 3 days

TDN = 0.725

Calculations:

Average QFAG = (2.68 kg/day) (3 day) (0.725) = 5.73 kg

Absorption rate = (1.34 kg/feeding) (1 feeding/12 hr) (0.725)
= 0.08 kg/hr

CNDIGG = Absorption Parameter = $\frac{0.08}{5.73}$ = 0.014

Depressed Digestibility

Although the simulation of the data available did not require a function to reduce the digestion of grain as the energy intake increased, the evidence in the literature indicated that, if possible, this aspect should not be left out of the final model. Witz secured the original data used for the creation of Figure 7 which shows the effect of level of intake on digestibility of various diets by cattle. Upon close examination of the data, Witz discovered that Figure 7 is somewhat deceptive. The figure represents relative digestible energy of diets and shows the relative value of hay above the relative digestible energy values of grain which decreases as the level of energy intake increases. The decrease in grain digestibility is evident in the data but the digestible energy values of the grain rations are higher than the digestible energy values of the hay. A clearer picture of the effects of level of feeding upon digestible energy would be for the grain values to start higher and decrease to slightly above the values for forage at high energy intake levels.

Because the data clearly indicated a depression of digestibility of grain as the level of feeding goes up and because the model increased the energy intake by eating longer, addition of a parameter to speed up excretion rate as a function of eating time was the best method of implementing decreased digestibility as level of intake increases. Physiologically this relationship is rational because the gastrointestinal reflexes stimulate bowel movement when the rumen refills during eating. The provision to implement decreased digestibility was included in the final model with the parameter set to zero. Determining the magnitude of the parameter and vertification of this modeling is still required.

The earlier models of the digestive section had a configuration in which only the amount of food, on a carbohydrate equivalent basis, reported in the literature as total digestible nutrients, TDN, entered the rumen. Essentially there was no excretion from the stomach of the earlier models because this was subtracted before the food entered the rumen. However, the provision to allow for decreased digestibility required an excretion rate from the rumen.

Because most feeds are defined on a carbohydrate equivalent basis, TDN, it was desirable to use this number as a method of establishing the excretion rate so that the necessary amount of food energy would be left in the stomach to be absorbed into the body. The excretion rate, like the absorption rate, was assumed to be a function of the weight of food in the rumen. Because the food absorption rate and the excretion rate both drained the rumen, the ratio of the total food weight absorbed to the total food passing through the rumen and intestines is equivalent to the total digestible nutrient value reported in the literature.

$$\mathrm{CNTDNG} = \frac{\mathrm{CNDIGG} * \mathrm{QFAG}}{(\mathrm{CNEXGA} + \mathrm{CNDIGG}) * \mathrm{QFAG}}$$

From this relationship the solution for the excretion parameter is a simple algebraic manipulation. Implementation of this calculation in the model resulted in the same responses as previous simulations having no excretion from the rumen and intestines. This configuration allows insertion of the TDN value as a food descriptive parameter and the correct excretion rate is computed during simulation.

CHAPTER VII

CHEMICAL SECTION

Model for Fatty Acid Synthesis

The chemical section of the beef model implements the conversion of the food energy absorbed into those fractions of energy associated with acetate and higher carbon molecules. The absorbed food is first reduced by the weight, on an equivalent carbohydrate basis, that goes into gas and urine production. These values are considered losses the same as the excretion, and are defined by constant parameters. The remaining weight of the absorbed food molecules is then converted into energy. A specified fraction of the energy is then deducted in the form of the heat increment of digestion. This digestive thermal energy is retained but deducted from the chemical energy and inserted directly into the thermal section of the model.

The absorbed food energy is then split into that energy represented by acetate molecules and that energy represented by higher carbon molecules. These molecules include both the higher carbon fatty acids and the carbon skeletons of amino acids which are assumed to pass through the Kreb's cycle during growth. The energy required for basal metabolism, PBMRZ, is removed from the acetate energy pool. The integral of acetate energy, EACT, is a state variable indicating the potential energy from acetate.

The energy from higher carbons is represented by a state variable, EHCAR, in a module configuration similar to a first order lag. The rate parameter of this module represents the rate at which the higher carbons enter the Krebs cycle and become net growth components or are oxidized for energy.

To calculate the higher carbon power that must be used for growth, the growth rates of each body tissue are multiplied by the estimated power required to produce growth. Witz, during calibration of his growth model, came to the conclusion that the energy value reported for protein and bone was on a dry matter basis whereas the weight of protein and bone to be modeled represented a living weight including water. For this reason, the energy value to produce a unit weight of flesh, which is approximately 18-20% protein, is about one-fifth of the energy value usually reported for protein. These lower energy values for living tissue weights were used.

A module of FORTRAN programming was used to deduct the power required for growth from the higher carbon power. The remaining higher carbon power was then assumed to be equivalent to acetate power and was inserted into the acetate energy pool. If the power to grow exceeded the higher carbon power available, the FORTRAN module used a portion of the acetate energy for power to grow. In this case it was assumed that the acetate energy was supplying only the power for growth and not the components.

The reaction of the model during various simulations showed that the possibility of the growth power exceeding the higher carbon power is very limited. It happened only on those occasions when simulations of fasting animals were made. In these cases the power, coming from the fat tissue, entered directly into the acetate pool and the animal continued to grow skeleton and tissue at the expense of fat. Schematic diagrams of the chemical section model and CSMP listings are located in Appendix VIII.

Parameter Calculations

The model for the chemical section was assembled with parameters to define the efficiency of chemical conversion and biochemical synthesis. The model was qualitatively tested using values for these parameters that were inserted by a best guess procedure. After the qualitative performance of the beef model was verified the values of the chemical parameters were refined. The calculation procedure followed the examples in Hafez and Dyer, 1969, with supporting data from Lehninger, 1970, and Blaxter, 1962.

Because the chemical section had a configuration in which the power for basal metabolism was removed from the acetate energy pool, all of the parameters of energy from chemical fuel, which would be converted to energy for maintenance, were considered to be zero. The basal metabolic power represented that power required as thermal energy to maintain body temperature. Therefore, any conversion of chemical fuel to energy for maintenance would eventually result in complete conversion of that fuel to thermal energy. So the parameters for the conversion of fat and for the use of higher carbons for energy for maintenance were set to zero.

The inefficiency of higher carbons used for growth components was calculated in two stages, the inefficiency of converting the higher carbons to Kreb's cycle intermediates and then the inefficiency of converting Kreb's cycle intermediates to synthesis of tissue, skeleton and fat. Chemical bond breaking is the major contributor to the inefficiency of converting higher carbons to Kreb's cycle intermediates. Using the thermal energy value for the chemical breaking of bonds, and comparing the results to the data for the energy of the propionic acid molecule and the energy recoverable from acetyl CoA, resulted in estimations of the inefficiency of higher carbon conversion to acetyl CoA being in the range of 2 to 4½%. The higher values resulted from estimation of the energy in the molecules by assuming an average energy value for the ATP production if the molecules were completely consumed. The reported energy values were different than the estimated values so the two percent value was used in the model. Values of 8% were used for the inefficiency of converting chemical intermediates of the Kreb's cycle to skeleton and protein. Hafez and Dyer, 1969, reported 8.2% inefficiency for converting glucose to fat. However, the biosynthesis of skeleton and of protein is a complicated procedure. Logically, the heat increment of this synthesis could be at least as large as the heat increment of the synthesis of fat.

The heat increment for synthesis of fat from acetyl CoA was calculated to be slightly lower than the 8.2% Hafez and Dyer reported for converting glucose to fat. This calculation was made by determining the loss in ATP molecules for each acetyl CoA molecule assembled into fat and then recovered as acetyl CoA. The inefficiency of the total biosynthesis and catabolic cycle for fat was approximately 10.4% of the energy. It was assumed that synthesis would take slightly more energy than catabolism. Therefore, a value of 60% of the heat loss was contributed to synthesis. The resulting heat increment for fat synthesis ranged from 6.24 to 7.25%. The higher value was selected.

Using primarily the data on the molecular ratio of acetic and propionic acid from Blaxter, 1962, the molecular ratio of the grain ration in the Missouri study was estimated to be about 45% acetate and 55% propionic acid. These percentages were multiplied by the energy value of the respective molecules. Then, the ratio of the acetate energy to the total energy was computed, with an adjustment being made for the amount of energy provided by the protein in the ration. Twelve percent protein was assumed. The results indicated that, for the rations used in the Missouri study, the percentage of energy going directly into acetate from grain was 57.7%.

CHAPTER VIII

COMPLETE MODEL

Qualitative Reactions

After the refinement of the digestive section, especially the digestive lag of newly eaten food, and after the development of the chemical section to produce a forcing function capable of controlling growth rate, the complete model was assembled and tested for compatability of the major sections and their interconnections. Also, these simulations were the first test of the minor modifications like the basal metabolic rate controller and the power from fat catabolism. The first simulation outputs indicated that the model could function without instability and that the model could simulate eating, growth and thermal transfer.

Although there were several parameters within the model that had been inserted as a best guess with no attempt, at this time, to verify their magnitude, the complete model was run through a series of qualitative tests to determine the general response. The qualitative simulations indicated that the model ate as planned. Whenever the blood acetate dropped below the set point, the model ate until the acetate concentration again exceeded the set point. The dynamic overshoot caused by the digestive lag and other lags in the growth and chemical sections resulted in enough changes in the acetate concentration of the blood to drive the growth section. Thus the model grew as a function of the average concentration of acetate in the blood.

The model did maintain a set temperature by using an increased output signal from the metabolic rate controller to modify basal metabolism. When high environmental temperatures were simulated, the metabolic rate controller shut off and the body average temperature rose above the set point temperature corresponding to data showing rectal temperature rise in high temperature environments. Several simulation trials were made of this phenomena and these assisted in establishing the basic metabolic rate to maintain body temperature with a minimum signal from the metabolic controller.

Qualitative change in blood volume as a function of temperature was also verified and this module appeared to function as expected. The simulations also showed that the model tended to gain more weight when it was fed on grain than on hay. This condition, correlating to common knowledge, was encouraging because the opposite reaction from the simulation would have indicated definite problems in the modeling. An added qualitative verification that the model was responding correctly, was the fact that the simulations showed that eating hay alone kept the model warmer than eating the grain ration.

The model of the beef animal was also starved by setting the eating rate equal to zero. The model responded by utilizing enough fat to maintain its body temperature and to continue to grow skeleton and meat tissue. The module for power from fat catabolism appeared to function as expected. The resulting simulation showed that as the blood acetate concentration dropped, fat would be utilized until a blood acetate concentration was established which caused a fat utilization equivalent to the thermal demand.

This was the first time that computer implementation of the humidity and radiation functions of the environment had been added to the model. Previously, humidity ratios and the radiation power had been defined as constants. A check of these functions indicated that they performed as expected.

As discussed before, additional control from metabolic controller had to be used as the body grew larger. This trend was contrary to the expected results. Also contrary to expectations, was the decrease in rectal temperature as the environmental temperature increased. These results indicated that the thermal model response to high temperature environments was not completely acceptable. At this time in the study, a decision was made to concentrate on the verification of the complete beef model from the data of the Shorthorns raised in the 50 F environment, and to postpone the solution of the thermal model irregularities. Part of the justification for this decision was the realization that the Shorthorns raised in the 80 F environment were so overstressed that the physiological responses were highly non-linear, as verified by the data shown on the ventilation ratios in Figure 23.

The qualitative simulations also served to discover minor programming errors and to reveal configurations that would be more convenient. While the desired revisions were being made in the model and calculations were being done to define some of the guessed parameters, the use of an optimization routine to determine the remaining unknown parameters was desired. The conjugate gradient optimization routine that Witz developed to optimize the growth section was added to the model program and the complete package was reloaded onto disk. This procedure made both the model and the optimization routine available for series of optimization runs and simulations without the time and expense of compilation.

After sorting through the unknown parameters, the list was eventually reduced to six that could not be defined or estimated from data. Three of these parameters, ERA, ERB, and CNERF, were related to the eating rate of grain and forage as a function of weight. Another two of the parameters, CNVPR and CORVPR, were related to the coupling of the chemical section to the growth section to provide the desired amount of growth.

A third variable, ACTREF, the set point level assumed for the acetate concentration in the blood where eating began and stopped is also involved in the coupling between the chemical section and the growth section as well as between the chemical section and the eating module. To reduce optimization cost this variable was arbitrarily fixed by selecting a set point within the reported concentrations of acetate in the blood. Research reports of acetate concentration in the blood ranged from two mg/100 ml to approximately fifteen mg/100 ml in larger beef animals. Younger animals have even higher concentration of acetate in the blood. The value of five Kcal/kg was chosen because it appeared to fall in the center of the normally reported range of acetate energy concentration in the blood for beef animals. This fixed parameter caused the value of the other constants coupling the chemical section and the growth section to be optimized as a function of this arbitrary choice. If an acetate concentration set point does exist, as postulated by this model development, its verification is still required.

The sixth unknown parameter was the rate of higher carbon use within the body. The value of one had been chosen, at random, in the earlier qualitative simulations. At the time of the optimization, no known relationship existed which could be used for an estimation of this rate.

Later experience with the model indicated that this parameter should be adjusted until the energy potential from higher carbons is slightly lower than the energy potential of acetate. This situation is approximately analogous to the reported ratios of the two energy potentials in the rumen.

The data selected to determine the performance index was the growth and feed data of the Shorthorn animals raised in the 50 F environment at Missouri. Because of the limitation on grain at 225 kg, it was decided to use data from 250 kg to the end of the study at 362 kg. This selection avoided the confusion in the amount of feed eaten when the animals were switched from an ad lib feeding to a controlled grain feeding.

The model of the beef animal, as assembled, required excessive computer time to simulate one day's growth. The average time was approximately one second, computer time, per day of growth. An optimization covering nearly 190 days would have been expensive. For this reason the performance index calculations for the conjugate gradient optimization were altered to allow three sub-runs within a single run to establish a performance index. This allowed the selection of three of the reported data points from Missouri at 253.4 kg, 313.5 kg and 360.9 kg to be used. The slope of the growth curve, and the average feed consumption at these points were used as the desired values. From previous simulations, the length of the sub-runs needed to establish a valid growth rate and feed consumption rate was chosen to be four days. This method of calculating the performance index thus used data points spanning the length of the growth curve but involved only twelve days of simulation instead of the required 190 if only one sub-run had been used.

Previous simulation experience with the model and some fortunate mathematical calculations resulted in a selection of initial values for the parameters close to the final values calculated. Therefore the excellent optimization routine was able to reach the final parameter values in a minimum of steps. The final result of the first optimization of the complete model is shown in Table VII. The largest deviations from the performance index values were for the growth rates which were apparently not weighted heavily enough and for the grain consumption which was a function of the integration time. Although the grain consumption was limited, the use of six minute integration intervals may have caused some deviation from the exact limitation.

The Missouri data for the growth of the beef animal from 253.4 kg to 322 kg, a time span of seventeen weeks, are shown in Figure 36. Also shown in this figure is the curve calculated during a simulation using the optimum values of the parameters. The growth curve shown for the simulation came within 3.8% of the final growth reported. More significantly, the growth curve is a convex curve when compared with a straight line, and closely resembles the reported data curve.

The results of this optimization verified that the model of the beef animal developed could be optimized to simulate a given set of growth data using energy definitions of the feed. Day by day knowledge of the amount of food to be eaten is not necessary for the simulation prediction of growth rate, because the model establishes its own estimate of the food it needs to eat. Present mathematical estimations for growth are based on the amount of food eaten. The food eaten must be known or estimated.

TABLE VII

COMPARISON OF BEEF MODEL TO MISSOURI DATA @ 50°F

	INPUT				GROWTH	
	Grain		Hay			
Weight (kg)	Data (kg)	Sim* (kg)	Data (kg)	Sim* (kg)	Data (kg)	Sim* (kg)
255	10.91	9.87	12.36	13.38	2.98	2.5
315	10.91	10.01	16.18	16.75	2.53	2.33
360	10.55	9.95	19.27	18.78	2.25	2.15
Totals	32.37	29.83	47.81	48.90	7.76	6.98
Error		(-2.54)		(+1.09)		(-0.78)
% Error		7.8%		2.2%		10%

*Simulation of 4 days compared to average data values for each weight.

However, simulation, using the optimum values calculated, revealed some discrepancies from the data. For one thing, the hay consumed by the model during simulation was about 20-25% lower than the Missouri data reported. Another problem that existed was that the model ate only every 26 hours instead of at least twice a day which would have

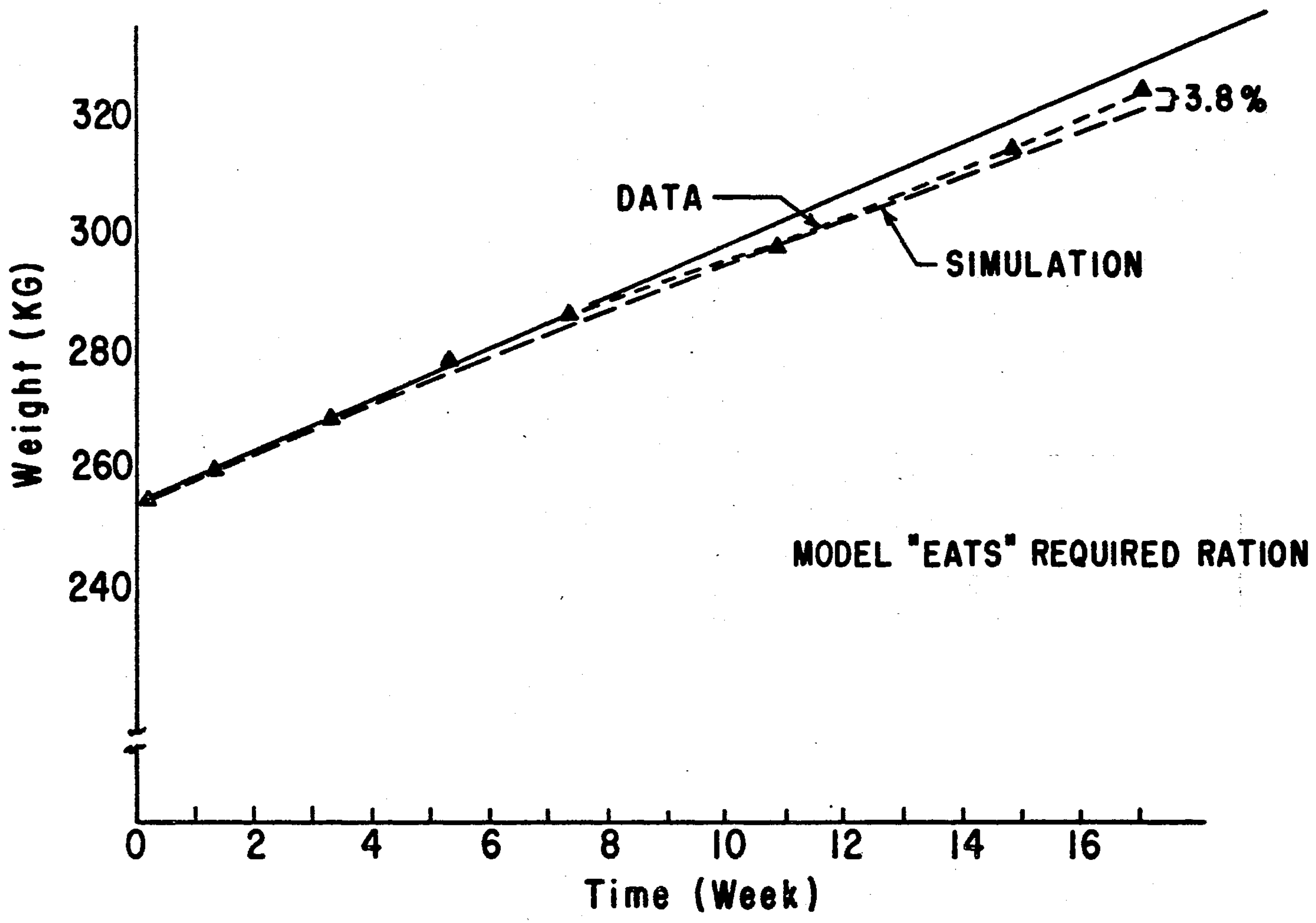


Figure 36. Comparison of the simulated growth predicted by the model compared to the original data.

been more desirable.

While the reduced amount of forage intake during the simulation was puzzling, the length of time between the eating periods was the more serious difficulty with the model. Several simulations, over four day periods, were run to attempt to reduce the length of time between feeding periods. The instantaneous values of power flow within the chemical section were plotted as various parameters were adjusted. Two parameters appeared to affect the time between eating periods. These were the eating rate and the rate at which higher carbon energy was made available. The original choices for these values were apparently an eating rate for the model that was too high and a rate of higher carbon availability that was too low. The optimization routine then found a local minimum in the performance index which required 26 hours between eating periods.

New estimates of the eating rate and of the rate at which higher carbons became available brought the length of time between feeding periods to within 12 hours. Also, the plotting of the instantaneous power flow within the chemical sections partially solved the puzzle of the reduced forage intake. The selection of the initial conditions for the potential of the acetate energy and the potential of the higher carbon energy resulted in transient power flows during the first day of simulation. These transients affected the control of the eating times. Usually they resulted in the model eating a higher amount of forage during the first day than it did on following days. The performance index calculation procedure, that had been used, resulted in a performance index that included the unusual amount of forage eaten during the first day because of these transient power flows. During simulations of several days growth, when the effect of the first day was reduced, the amount of forage eaten by the model was lower than the data by approximately the difference caused by the unusual first day consumption in a four day feeding period.

Revision of Model and Optimization Packages

Although the model and the optimization routine, stored on disk, reduced compilation time and expense, this arrangement fixed those parameters chosen for optimization and those chosen for the performance index criteria. The experience with optimization and the simulation revealed that a method which would allow selection of any of the parameters for optimization or for performance index criteria would be desirable.

Furthermore, the slowness of the complete model in optimization routines made it desirable to speed up the integration calculations. The simplest form of integration, rectangular integration, was already being used. Experience on previous simulations had indicated that the integration interval could not exceed three minutes (0.05 hours) for animal weights less than 225 kg nor should the integration interval exceed six minutes (0.1 hours) at weights above 225 kg. Also, Witz desired an option to enable use of a grid search routine to reveal local minimums in the performance index. The possibility of using the optimization routine for management decisions was conceivable, provided general access to any of the parameters for optimization or variables for performance index criteria was made available.

For these reasons, the entire model and performance index calculation procedure was rewritten in a joint effort with Witz. As it then existed, the complete model involved twenty-five integrators, two of these being used for output purposes only. Some integrators were associated with state variables that varied with a rapid frequency. It was these integrators and their high frequency output that restricted the integration interval to 0.1 hour or below. However, there were several integrators serving primarily as summing integrators, which had a slow rate of change in the output variable. The calculations made from outputs of these integrators, in the UPDATE subroutine of the CSMP execution phase did not have to be repeated every integration step.

Acting upon Witz' recommendation, all of the integrators were left to be updated every integration interval because the simplest integration routine, rectangular integration, was already being used. Then the output of each integrator was classified as fast or slow. The eventual division of the integrator output classification was into four categories:

1. Integrator output changing so slowly that new calculations based upon these values are required only at intervals greater than a day.
2. Integrator output values that should be sampled daily.
3. Integrator output values that should be sampled hourly.
4. Integrator output values that required sampling every integration interval.

A fifth category was also created because a large block of calculations associated with the eating function needed to be recalculated every integration interval during eating mode but did not need to be updated more than hourly during the period between eating. An offset signal was arranged so that, as the acetate concentration in the blood approached the eating set point, this section of computations was switched from the hourly update section to the section being updated every integration interval.

After the outputs of the integrators had been classified with respect to their sampling interval, each of the calculations that made use of the output were put into the same section. In cases where the FORTRAN equation involved calculations using variables from the high frequency and the lower frequency update sections, the equation was divided. A new variable was created so that all of the calculations that could be done in the slow frequency section were performed. Only an addition of the new variable was done during the high frequency computations.

This identification and division of computations was accomplished. Also some refinements in the original complete model, such as the elimination of the digestive lag during non-eating periods, were also made. Then a simulation was run to insure that the output of the revised statements matched closely to the previous output of a verification run made before this major revision.

When verification was accomplished the UPDATE subroutine created by the CSMP translation phase was used as a guide for an UPDATE subroutine created manually. The manual operation included resorting the FORTRAN statements into their respective categories based on frequency of computation. The CSMP functions, such as the comparator, the inclusive or logic module, and the delay function, were replaced with simpler forms of FORTRAN programming to eliminate the necessity to call subroutines. The most extensive reorganization was the reordering of the variable names within the COMMON block of the subroutine

UPDATE.

This reordering was done to secure user convenience of the program as well as to make possible faster computation. Witz wrote a stand alone FORTRAN routine that created a default data set on disk. Another stand alone FORTRAN program, also written by Witz, was used to load the default data set with the correct parameters. Then Witz wrote a new main program, to be used with the CSMP routines, which initialized the model from the default data set having the correct parameters. Then, the main routine called the CSMP INTRAN subroutine which would read those CSMP data cards desired by the user. This approach allows the user to insert only those parameters that required change and eliminated CSMP translation of approximately 150 constants that are not changed between successive simulations.

An option in the main program written by Witz allows the user to enter parameter values in data cards having formats defined by the main program. This option allows users to insert or change data in the COMMON area by defining the location and then entering the data value desired. This feature is particularly useful when inserting strings of data for use with the optimization routine.

The sort of the UPDATE COMMON area was made to match the requirements of the operational programs created by Witz. Also two other objectives were met during the sort. The COMMON area was allocated into integrator output, integrator inputs, initial conditions for the integrators, INTRAN data, likely data constants inserted by the FORTRAN formats, and likely output variables. Within the designated subareas the order of the placing of the parameter or variable names was such that more frequently called variables for input or output were placed first in the section. This order was followed so that the routines for input and output would not have to search the entire COMMON area to find the names. Furthermore, functionally related parameters were grouped together. For example, those parameters used in feed description were grouped in one area and the parameters used to describe the environment were grouped in another area. This arrangement was for user convenience while inserting data by the format data cards. In some cases, parameter names were made equivalent to a storage table so that the entire listing of the parameters could be inserted as a string of data, but could be used within the UPDATE subroutine as named parameters. Grouped last in the COMMON area were all of the internal variables not likely to be called upon for output. These were not grouped functionally but were arranged alphabetically because there was no necessity for a definite order. Appropriate dummy areas were left in the COMMON block to facilitate changes of the program without requiring extensive rearrangement of the COMMON area. The wisdom of this provision was quickly proven as execution revealed minor changes required in the programming. When the order of the words in the COMMON area of the subroutine were established, the packed symbol table was also written by hand to correspond to the revised COMMON area of the UPDATE routine. The CSMP execution phase uses the packed symbol table for identifying the storage location of input and output variables requested by the user.

A generalized parameter selection and performance index calculation procedure was written and checked in FORTRAN before it was added to the UPDATE routine. The same procedure was followed for a grid search routine which was written by Witz. The method for gaining access to any of the parameters for optimization or variables for performance index calculation was to use a single dimension array of the same size as the COMMON area in the UPDATE routine. This array, called the C array, was set equivalent to the COMMON area. Thus any subscripted item from the C array was equal to the parameter or variable at that location in the COMMON area of the UPDATE routine. This allowed the selection of any parameter for optimization or any variable for performance index calculation. The index values to define these parameters were given variable names which were defined during optimization runs by inserting data through the formatted input section of the main program.

The experience, gained with previous optimization runs, had revealed the necessity of having at least two types of performance index calculations. One type required successive performance index calculations against desired values along a curve produced during simulation. The second type of performance index involved only terminal values of the variable compared to desired terminal values. This type of performance index calculation might require three or more sub-runs to reduce optimization time and expense. Both types of these performance index calculations could be squared-error calculations with weighting constants. For management optimizations, a third type of performance index calculation was foreseen. This type is a performance index involving an output variable and its associated cost.

When the requirements were established, the FORTRAN programming was accomplished, with necessary storage areas and variables allowed, to allow the user to select any or all types of performance index calculations with up to five output variables within each type of performance index mode. When the total performance index is calculated by the present program, the user has a choice of selecting either conjugant gradient optimization or grid search sequencing for performance index computations. If a grid search is specified, with only one point defined in the grid, a performance index calculation associated with a single run is achieved.

Another refinement to the optimization routines was the establishment of a tare section and associated output variables. This routine allows the model to be run for a given period, usually one day simulation time, and then tare values are taken for those variables that might be affected by the transient conditions during the first day of simulation time. This refinement reduces the probability that the transient conditions of initialization of the model will not be reflected in the performance index calculations. A flow chart of the parameter optimization and performance index calculation routine is shown in Appendix I. The listings of the FORTRAN statements for these routines are included with the final model listing in Appendix I.

Second Optimization

When the restructured model and the associated optimization packages had been validated against the verification copies of the previous model, a second optimization was made using the same Missouri data with an additional performance index variable, the net number of times the model animal ate, FEDN. This second optimization required use of both the grid search and the optimization routine. By this time, the required value for the parameter defining higher carbon availability rate was established. This value was dropped from the optimization and the second order constant of the eating rate function added so that the eating rate was better defined by a second order polynomial equation. During this optimization the grid search revealed that the first solutions were a local minimum and that better performance index values existed.

The problem appeared to be with the initial constants included in the eating rate function. A simulation was run with the eating rate constants defined at the local performance index minimum. Then the results were used to calculate the value of the eating rate constants that would have produced the desired values of the performance index variables. A curve, established manually through these data points and extended to the extremes of the animal weight range, was then defined by a polynomial equation. The new constants in the polynomial equation were used to establish the eating rate as a function of weight. These new constants provided a better performance index and further optimization made only a slight change in their estimated values.

Figures 37 and 38 show part of the output of the optimized model as it compared with the original Missouri data. Most of the other variables duplicated curves already shown, so only a sampling at 5 week intervals is shown in Table VIII for verification.

The major discrepancies between the simulation output and the original data were a low total metabolic rate at the start of the simulation and a lower consumption of hay throughout the entire simulation run. The low metabolism of the simulation was, probably, caused by the improper assignment of heat generation rates to the tissue components and, perhaps, by an inadequate selection of the

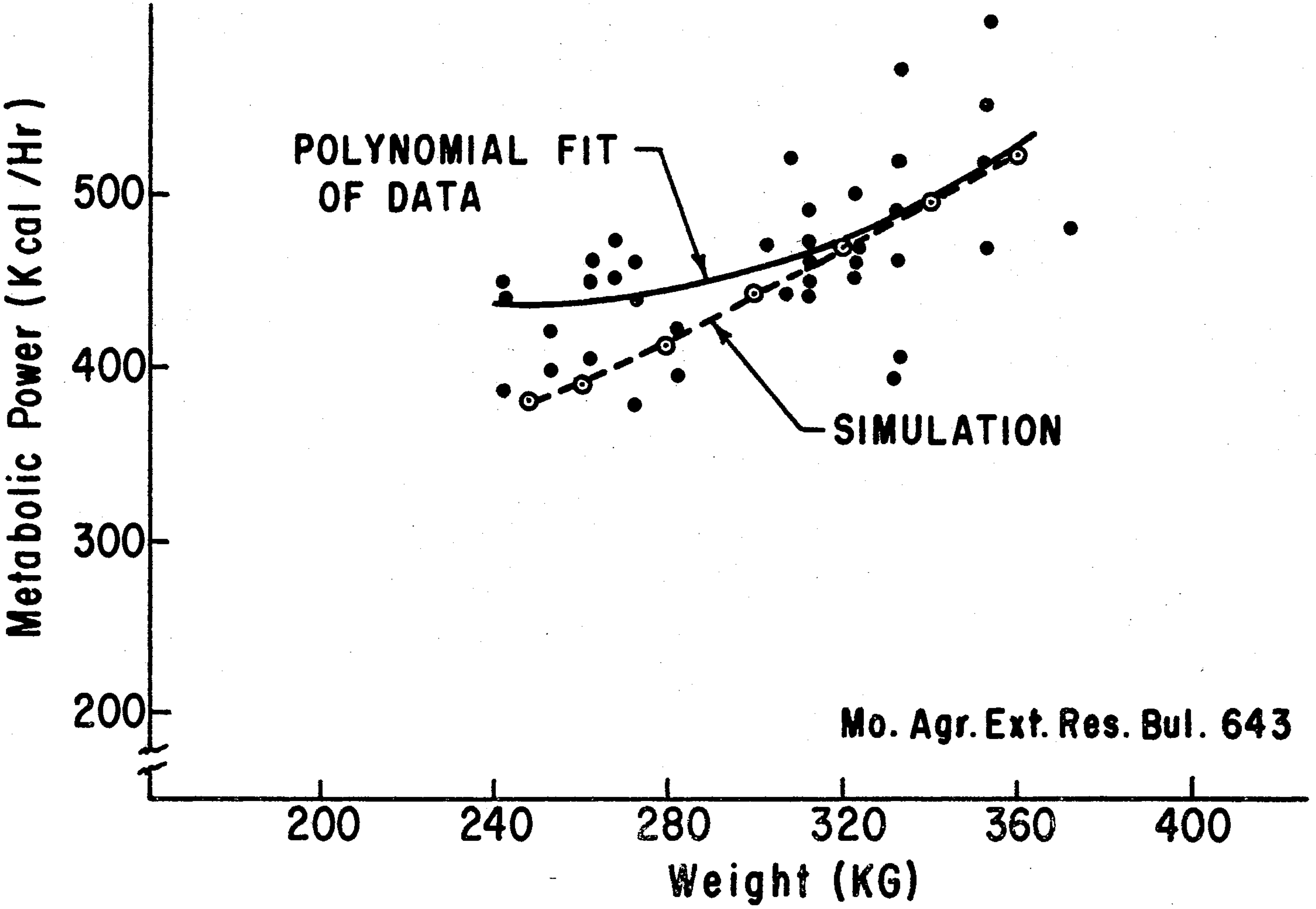


Figure 37. Comparison of the metabolism predicted by the final model to the original data.

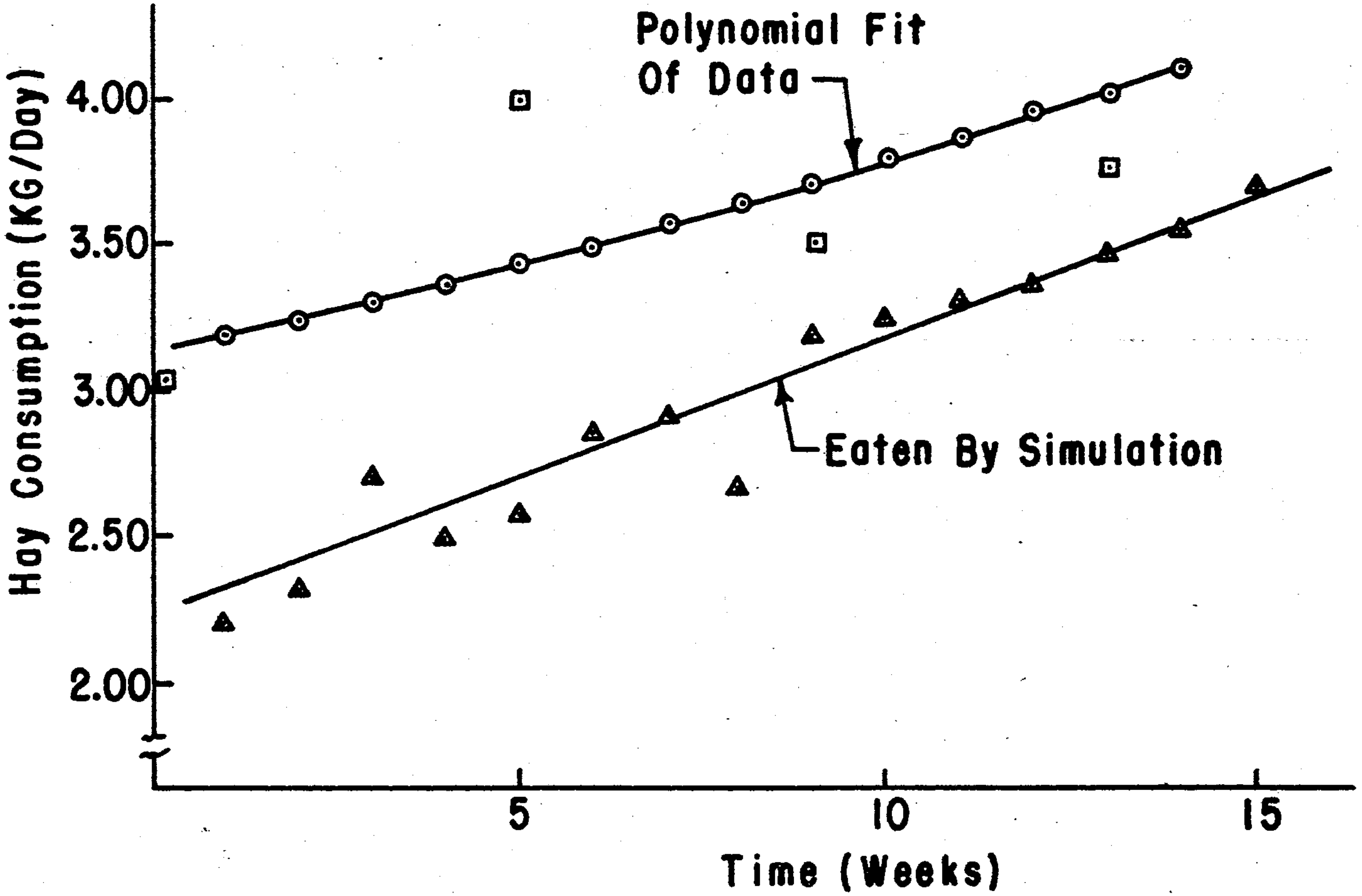


Figure 38. Simulation estimate of hay consumed compared to data.

basic metabolic heat generation rate. The low hay consumption was probably caused by an incorrect choice of the heat increment of hay digestion. Apparently the maximum value reported by Blaxter, 1962, is too small to enable the model to simulate the required growth and hay consumption. An increased heat increment of digestion would cause the model to simulate eating more hay to produce the same amount of growth.

TABLE VIII

SAMPLED DATA FROM MODEL VERIFICATION SIMULATION

	WEEKS					
	1st	5th	10th	15th	20th	25th
QAW (Kg)	257.5	274.2	294.7	314.7	334.6	354.1
PRDOUT (Kcal/hr)	121.1	128.5	138.5	148.4	159.1	169.5
PHEOUT (Kcal/hr)	166.4	178.3	191.3	201.4	212.8	221.0
PSVOUT (Kcal/hr)	53.89	57.35	61.69	65.95	70.55	74.93
PRVOUT (Kcal/hr)	42.2	45.3	48.1	49.8	51.2	51.8
TG (°C)	39.27	39.29	39.29	39.27	39.25	39.22
TS (°C)	32.64	32.62	32.60	32.59	32.59	32.60
TH (°C)	23.32	23.34	23.33	23.26	23.21	23.11

The restructured model increased integration speed at least five times. Therefore, the full 190 day growth from 253.4 kg to the end of the growth period for Shorthorns was simulated. All of the output variables shown in Figure 37 and 38 and Table VIII were computed in 44.65 seconds at a cost of $8.07. In effect this simulation run reproduced a half year of research data. As it now exists the Shorthorn default data can be used to dynamically demonstrate 190 days of energy metabolism in Shorthorns raised in an environment of 62% relative humidity and 50 F temperature. The effect of parameter changes, within 10% of the present values, should dynamically simulate the response of the Shorthorns to the new conditions.

Proof of Model Against Other Data

The most expedient proof of the model against other data was accomplished by making a simulation of the Shorthorn animals raised in the 80 F environment. A sampling of the output from the simulation is compared to the original data in Table IX. The simulation prediction of skin temperature, hair temperature, and growth rate compare favorably with the data. The metabolic rate begins low and rises to the reported level at the end of the eight-week simulation. This response also indicates that the modeling of the heat generation rate per unit volume is still inadequate. In this simulation, the basal metabolic controller did not function because the average body temperature was above the metabolic controller set point of 37.22 ^{o}C.

Significant deviations of the simulation output from the original data occurred with the predictions of the heat loss by respiratory vaporization and by skin vaporization. The major dis-

TABLE IX

SAMPLED DATA FROM HIGH TEMPERATURE ENVIRONMENT SIMULATION COMPARED TO REPORTED DATA FROM MISSOURI

	1st Week		4th Week		8th Week	
	Model	Data	Model	Data	Model	Data
QAW (kg)	257.5	257.0	270.3	272.0	286.9	293.7
POWER (Kcal/hr)	318.4	394.0	369.78	400.0	417.6	410.0
PRDOUT + PHEOUT (Kcal/hr)	178.1	169.0	193.6	167.0	227.6	168.0
PSVOUT (Kcal/hr)	66.2	160.0	71.4	165.0	82.3	170.00
PRVOUT (Kcal/hr)	74.2	65.0	94.8	68.0	107.9	72.0
TG (°C)	38.6	40.0	38.5	40.0	38.5	40.0
TS (°C)	35.5	35.5	35.8	36.6	35.8	36.6
TH (°C)	32.5	33.9	32.6	35.0	32.7	34.9
TAVE (°C)	37.5		37.7		37.7	
QEATFN kg/day	2.26	3.64	2.51	3.74	2.73	3.93

crepancy is caused by the low skin vaporization predicted by the simulation. Apparently the function for the moisture transfer coefficient was developed from data that did not involve active skin vaporization. Therefore, the moisture transfer coefficient, as a function of the average body temperature, has a smaller slope than is necessary to simulate skin vaporization in higher temperature environment. The discrepancy in the respiratory vaporization heat loss was expected because the respiratory heat loss responds linearly to a rise in the average body temperature and the Shorthorns raised in the 80 F environment were forced into nonlinear responses, as shown in Figure 23. Future development work on the thermosection should include recomputation of the skin vaporization function. The present model can incorporate the new parameters without structure changes. Quadratic formulation of the heat transfer coefficients as a function of the average body temperature should be done when the structure is revised. The quadratic formulation would enable modeling of the non-linear response at high environment temperatures.

The other major discrepancy between the simulation for the 80 F environment and the original data was that the rectal temperature of the animal decreased from the rectal temperature maintained in the 50 F environment. This is contrary to the data and apparently indicates the discrepancy of the assignment of the heat generation rates to the different body tissues. A higher heat generation rate in the gastrointestinal tract will result in a higher rectal temperature.

To demonstrate the potential use of the model in new environments and feeding situations, a simulation was made of the experiment by Taylor and Young, 1964. None of the data of this experiment had been used in the formulation of the model. Although Taylor and Young had reported periodic data that enabled establishment of the daily food intake and the daily gain of the calves, they had restricted the food intake in an attempt to make the animals grow at 1.25 pounds per day. However, during most of the time period simulated, the animals were fed ad lib because the growth rate was not maintained. A valid simulation required that the same restrictions upon feed intake be applied. This was accomplished by inserting the correct parameters into the food mode module to limit grain intake per day as a function of body weight. A polynomial equation fitting Taylor and Young's reported daily food intake was used to establish the necessary parameters to limit food intake. However, during the simulation, the model ate ad lib because the intake limit was never reached.

Taylor and Young had only described the ration fed and did not present any data that would enable the calculation of the energy contained within the ration. Average net energy values were calculated using the information by Gill, 1968. From these net energy values the equivalent carbohydrate basis of the feed was estimated by the formulas given in Crampton and Harris and verified against similar values reported for feeds having the same net energies and fibre content. This estimation of carbohydrate energy was then used as the energy value of the feed. Values for the heat increment of the feed and for passage of the feed through the animals were assumed to be similar to those established for a hay ration because the ration fed by Taylor and Young was over 66% grass or straw.

The simulation covered a reported time period of one year and one day. The simulation time was 45.61 seconds at a cost of $18.73.

However, the first four months of simulation required the use of a three minute integration interval because of the small size of the animal at the start of the run. The results of the simulation compared to the data reported by Taylor and Young are shown in Figure 39. For sixteen weeks, the growth rate indicated by the simulation approximated the growth rate of the best gaining group of six animals in Taylor and Young's study. At this point the simulation had an error of approximately 10.8 percent when compared to the mean value of the group of twelve animals. After the first sixteen weeks, the simulation growth began to deviate upward from the growth reported and eventually resulted in an estimated weight 6.8% higher than the weight of the fastest gaining animal. The simulation deviation from the mean weight of the fast growing group is just slightly larger than their deviation from the group of six animals that gained slower. When the growth data at the end of the simulation was compared with the mean value of growth for all twelve animals, the simulation data gave an estimate that was 47.5% higher. The simulation feed intake was consistently lower than the data. The maximum deviation was 29.5%

The deviation of the model from the data might be reduced by rerunning the simulation with different environmental temperatures then were used in this first simulation. Also, the growth curve indicates that the Ayrshire animals apparently approached mature growth faster than the Shorthorn parameters estimated.

Brody, 1945, shows mature weights of Shorthorn bulls to be 1100 kg and mature weights of 460 kg for Ayrshire cows. The difference in the hereditary parameters would be enough to enable the model to simulate faster growth beyond the 600 lb turning point of the data.

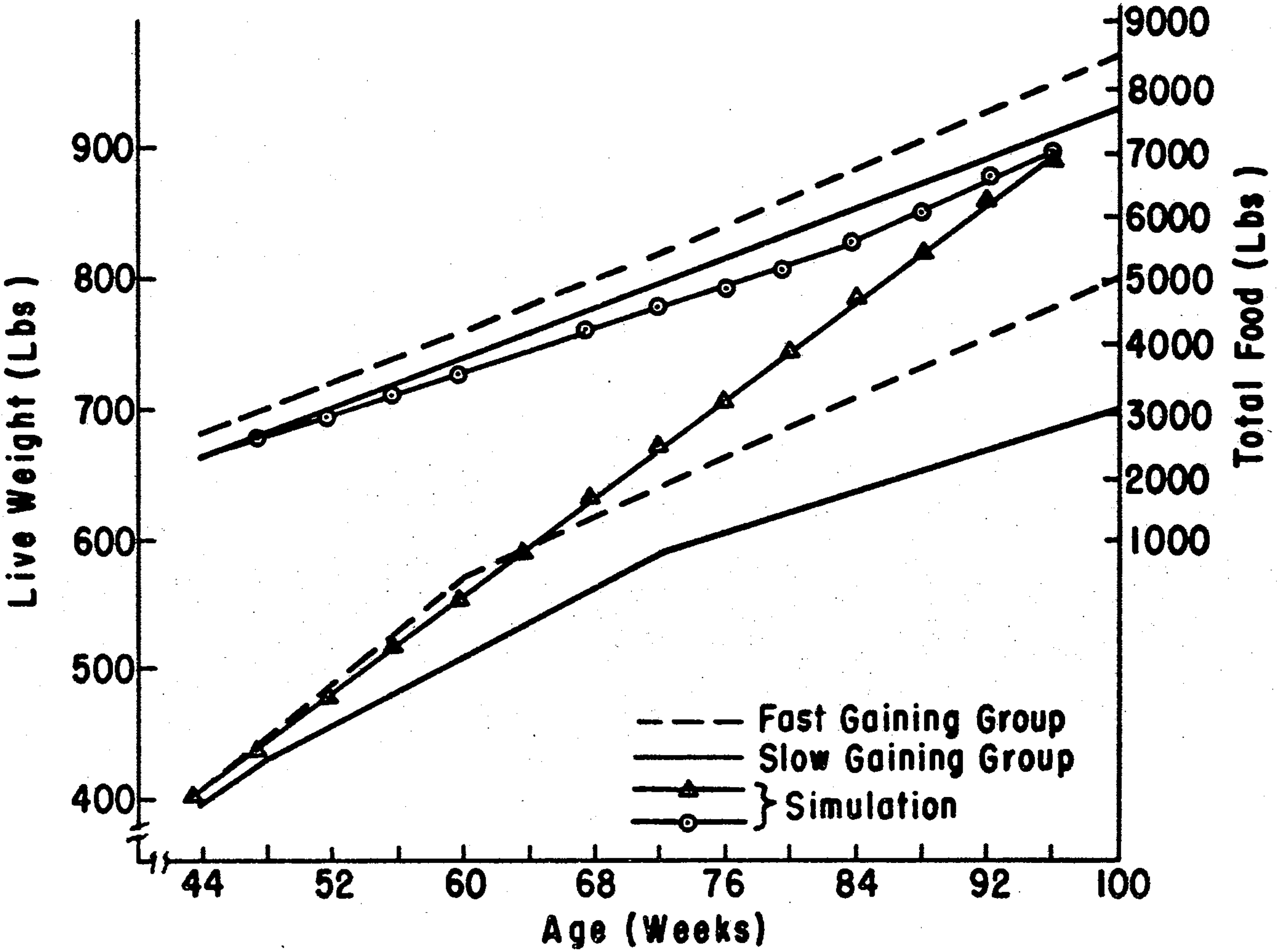


Figure 39. Shorthorn model prediction of Ayrshire growth compared to data not used in model formulation.

Certainly the model could be optimized to fit the data quite closely. Considering that there was limited data for defining the environment, that no estimate was made of breed differences and that the estimation of the energy of the feed could have been in error by 10 percent, the simulation shows that the model can be used for a prediction of animal growth, at least during a four month period. The model has possibilities of coming closer to the actual data if weather, animal breed and feed parameters are more explicitly defined than was done in this simulation.

CHAPTER IX

CONCLUSIONS AND DISCUSSION

Conclusions

The successful development of the model described in this report demonstrates that systems modeling techniques can be applied to energy metabolism in animals. The physical models utilized also appear to be functional.

The equivalent thermal cylinder is an acceptable physical model for heat transfer simulation. The major developmental work remaining is further clarification of the heat generation rates of each body component. The second order differential equations used for the growth model of each body component appear to be adequate and they do simplify the complex relationships of growth.

The digestive model with its first order lag and the chemical model with its division of carbon energy appear to be functional and to also represent recognizable quantities.

The complete model responds similar to a live beef animal. It can dynamically simulate eating, respiratory and skin vaporization, convective and radiation heat transfer, growth of skeleton, fat, meat, and offal, and catabolism of fat for energy.

The optimization routines employed in this development have been combined with the model to produce a potentially powerful management and research tool. This package can be easily adapted to a variety of data and situations.

The validation and comments on each section have already been discussed. The specific conclusions reached during this development are:

1. Systems modeling techniques can be used very effectively to develop improved models of energy metabolism in beef animals.
2. The model of a beef animal developed in this study will dynamically simulate 190 days of growth for Shorthorn heifers raised in a 50 F environment. The model can predict the response of these Shorthorns to changes in environment or feed.
3. The model developed can be used as a general predictor for other animals, fed other rations in other environments. The model did predict four months of growth of Ayrshires in Great Britain within the data range and 10.8 percent from the mean weight of 12 animals. The estimated feed intake for an entire year was within 29.5%. The estimated growth at the end of the year was 6.8% higher than the fastest gaining animal but 47.5% higher than the group mean.
4. The model could demonstrate dynamically the temperature distribution within growing beef animals. Also vaporization rates and ventilation rates were simulated in correspondence with the data.
5. The model and the optimization packages can be used as a research tool and also to assist in making management decisions for beef production.

Discussion

The creation of this model provides a new tool for research which presents new opportunities. The development of the model has raised questions that need further study and clarification. These include the heat generation rates of each of the individual tissue components of the body and the verification of the signal that is used by beef animals to start and stop eating. Some of the assumptions and hypotheses that had to be made in the model development also remain to be verified. These include the set point of acetate concentration in the blood for the eating function or for power from fat. Also the actual mechanism of the basal metabolic rate controller and the control mechanisms associated with heat transfer, particularly moisture transfer at the skin surface, remain to be verified.

Earlier simulations using only the thermal section of the model were compared to data by Kiesling, 1971, for the basal metabolism of fasting Hereford steers. The simulations indicated that the steers at three different weights maintained approximately the same average body temperature. These implications may mean that the mathematical model of a beef animal can be used in conjunction with basal metabolic studies to determine the animal's set point temperatures. The set point temperature in these studies might be defined as the average body temperature when there is no external energy input. This future use of the beef animal mathematical model in conjunction with animal science research on metabolism should be investigated further.

Also the model itself should stimulate research in efforts to further define the parameters of the model independently. For example, the coupling between the chemical section and the growth section of the model is a function of the acetate concentration in the blood. Research correlating transient concentration of acetate in the blood with food intake could be used to more clearly define parameters associated with the eating and chemical sections of the model. If these same transients of acetate concentration in the blood were correlated with the distribution of growth in fat, skeleton, meat and offal, the parameters in the growth section of the model could be better defined for a particular breed of animal.

Example of Management Optimization

The restructured model, as it now exists with its optimization routines, is a valuable research tool. Essentially, the model can be optimized to any type of data from concentration of blood acetate to the animal ventilation rate. As optimization is made on various types of data, the experience necessary to adjust the parameters of the model should become more developed.

However, one practical use of the model in feedlot situations would be to assist in the management. An example of the management possibilities is shown by Table X which summarizes the variable and fixed costs of operation as predicted by simulations of the Shorthorn animals raised in Missouri in the 50 F environment. As shown, a grain limit of 2.11 kg per day would result in minimum costs. This example is shown only to demonstrate the possibilities of management use of the beef model. Five levels of feeding of the grain ration were considered available to the manager with a cost of $4.50 per hundred weight of grain, $1.50 per hundred weight of hay, and with a fixed cost for building, labor, and interest of 5¢ per head per day. These costs were chosen to demonstrate the performance calculation routine. They are not valid prices. The cost of grain would usually be lower, and the fixed costs higher. The third section of the performance index computation routine, which calculates the cost of the variables, was used to estimate the total cost of growing the Shorthorns from 253.4 kg to 275 kg. In a feedlot situation, the primary optimization might use simulations which span similar weight gains. Total costs would then be calculated by using the optimum values of the parameters in a simulation to the desired final weight of the feedlot animals.

TABLE X

MANAGEMENT EXAMPLE, COST OF OPERATION VS. GRAIN LIMIT

Grain/Day (kg)	Net Days To 275 kg (Days)	Total Forage Eaten (kg)	Cost ($)
1.36	35.6	87.35	4.35
1.61	34.4	60.22	4.40
1.86	32.8	34.76	4.36
2.11	31.2	11.08	4.30
2.36	30.8	0.81	4.34

The model should prove, after further calibration, useful in feedlot situations. As shown above, the present model and optimization routines can now be used, to predict results of management decisions.

The present model can be adjusted to a particular breed, feed ration and weather conditions if one month of data is collected and used with the optimization routines to calibrate feed and animal parameters. Then, the model should serve as a predictor of performance for the remainder of the feeding period. Another optimization using the data from the complete feeding period would further refine the model parameters. This optimization over the entire feeding period would provide a better base for adjusting the hereditary parameters of the animals. Performance predictions for a new set of animals of the same breed with the same ration in similar weather should be fairly accurate.

The present model is slow and expensive to use for large management decisions involving multiple parameters. However, the model can be used to simulate responses to feed energy levels and to environment conditions. These responses could be used to develop a faster model using simplified equations to simulate the average physiological responses as a function of feed energy and time. This simpler model would smooth the high frequency variables and would allow integration intervals up to a week, instead of every six minutes. Thus, optimization of management decisions involving multiple parameters that may span six months or more could be within economic justification.

A SELECTED BIBLIOGRAPHY

Andersson, B., and B. Larsson, 1961, "Influence of Local Temperature Changes in the Preoptic Area and the Rostal Hypothalamus on the Regulation of Food and Water Intake", *Acta. Physiol. Scand.* 52:75.

Balch, C. C., and R. C. Campling, 1962, "Regulation of Voluntary Food Intake in Ruminants", *Nutr. Abstr. Rev.* 32:669-689.

Bedwell, R. L., and M. D. Shanklin, 1962, "Influence of Radiant Heat Sink on thermally-induced Stress in Dairy Cattle", *Mo. Agr. Exp. Sta. Res. Bull.* 808, Columbia, Mo.

Beckett, F. E., and C. Vidrine, 1969, "A Mathematical Model of Heat Transfer in a Pig", Paper No. 69-437 Presented at the *Amer. Society of Agr. Engineering* Meeting, Purdue Univ., W. Lafayette, Indiana.

Berry, I. L., and M. D. Shanklin, 1961, "Physical Factors Affecting Thermal Insulation of Livestock Hair Coats", *Mo. Agr. Exp. Sta. Res. Bull.* 802, Columbia, Mo.

Blaxter, K. L., 1962, *The Energy Metabolism of Ruminants*, Charles C. Thomas, Publisher, Springfield, Illinois, U. S. A.

Blincoe, C., and S. Brody, 1956, "The Influence of Ambient Temperature, Air Velocity, Radiation Intensity, and Starvation on Thyroid Activity and Iodide Metabolism in Cattle", *Mo. Agr. Exp. Sta. Res. Bull*. 576, Columbia, Mo.

Blincoe, C., 1965, "Design and Testing of a Hair Measurement Beta-Gauge", *Mo. Agr. Exp. Sta. Res. Bull.* 616, Columbia, Mo.

Blincoe, C., 1958, "The Influence of Constant Environmental Temperature on the Thyroid Activity and Iodide Metabolism of Shorthorn, Santa Gertrudis, and Brahman Calves During Growth", *Mo. Agr. Exp. Sta. Res. Bull.* 649, Columbia, Mo.

Bouchillon, C. W., F. N. Reece and J. W. Deaton, 1969, "Mathematical Modeling of Thermal Homeostasis in a Chicken", Paper No. 69-436 Presented at 1969 Annual Meeting of *Amer. Society of Agr. Engineers*, Purdue Univ, W. Lafayette, Indiana.

Brobeck, J. R., 1960, "Food and Temperature", *Recent Progr. Hormone Res.* 16:439-466.

Brockett, R. W., 1970, *Finite Dimensional Linear Systems*, John Wiley and Sons, Inc.

Brody, S., and E. C. Elting, 1926, "A New Method for Measuring Surface Area and Its Utilization to Determine the Relation Between Surface-Area Growth, weight growth, and Skeletal Growth", *Mo. Agr. Exp. Sta. Res. Bull.* 89.

Brody, S., J. E. Comfort and J. S. Matthews, 1928, "Further Investigations on Surface Area", *Mo. Agr. Exp. Sta. Res. Bull.* 115.

Brody, S., 1945, *Bioenergenics and Growth*, Reinhold Publishing Corporation, New York.

Brody, S., 1948, "Physiological Backgrounds", *Mo. Ag. Exp. Sta. Res. Bull.* 423, Columbia, Missouri.

Brody, S., H. E. Dale and R. E. Stewart, 1955, "Interrelations Between Temperatures of Rumen (at various depths), Rectum, Blood, and Environmental Air; and the Effects of an Antipyretic, Feed and Water Consumption", *Mo. Agr. Exp. Sta. Res. Bull.* 593, Columbia, Mo.

Brooker, D. B., 1966, "Mathematical Model of Psychrometric Chart", Paper 66-815, Presented at 1966 Winter Meeting, *American Society of Agricultural Engineering*, Chicago, Illinois.

Carslaw, H. S., and J. C. Jaeger, 1959, *Conduction of Heat in Solids*, 2nd Ed., Oxford University Press, Amen House, London.

Charette, W. P., A. H. Kadish and R. Sridhar, 1969, "Modeling and Control Aspects of Glucose Homeostasis", in *Hormonal Control Systems*, *Supplement 1*, *Mathematical Biosciences*, Ed. by E. B. Stear and A. H. Kadish, American Elsevier Publishing Co., Inc., New York.

Citron, S. J., 1969, *Elements of Optimal Control*, Holt, Rinehart and Winston, Inc., N. Y.

Crampton, E. W., and L. E. Harris, 1969, *Applied Animal Nutrition*, W. H. Freeman and Company, San Francisco.

Crosbie, R. J., J. D. Hardy and E. Fessenden, 1961, "Electrical Analog Simulation of Temperature Regulation in Man", *Ire Tras. Bio-Med. Electron*, BME-8(4).

Crosby, H. A., and M. K. Klukis, 1968, "Computer Simulation of a Nonlinear Blood Flow Model", *Fall Joint Computer Conference*.

Dale, H. E., G. J. Burge and S. Brody, 1956, "Environmental Temperature and Blood Volume", *Mo. Agr. Exp. Sta. Res. Bull.* 608, Columbia, Mo.

Dale, H. E., K. C. Ragsdale and C. H. Cheng, 1959, "Effect of Constant Environmental Temperatures of 50 and 80 Degrees F on Ovarian Activities of Brahman, Santa Gertrudis, and Shorthorn Calves with a Note on Physical Activities", Mo. Agr. Exp. Sta. Res. Bull. 704, Columbia, Mo.

D'azzo, J. J., and C. H. Houpis, 1966, Feedback Control System Analysis and Synthesis, McGraw-Hill.

Distefano III, J. J., and E. R. Stear, 1969, "Modeling and Control Aspects of Thyroid Function", in Hormonal Control Systems, Supplement 1, Mathematical Bioscience, Ed. by E. B. Stear and A. H. Kadish, American Elsevier Publishing Co., Inc., New York.

Esmay, M. L., 1969, Principles of Animal Environment, Avi Pub. Company, Inc., Westport, Connecticut.

Eveleigh, V. W., 1967, Adaptive Control and Optimization Techniques, McGraw-Hill, Inc.

Frahm, R. R., L. E. Walters and G. V. O'Dell, 1970, "Evaluation of Live Animal K40 Count as a Predictor of Lean in Beef Bulls", Progress Report, 1969-70, Animal Science Research, M. P. 84 Oklahoma State University.

Frandson, R. D., 1965, Anatomy and Physiology of Farm Animals, Lea and Febiger, Philadelphia.

Gill, D. R., 1968, "How to Use Net Energy Tables for Cattle Feeding", Leaflet L-167, Oklahoma State University Extension,Stillwater, Oklahoma.

Goss, R. J., 1964, Adaptive Growth, Logos Press, Academic Press. London.

Grodins, F. S., 1963, Control Theory and Biological Systems, Columbia University Press, New York.

Hafez, E. S. E., and I. A. Dyer (Eds.), 1969, Animal Growth and Nutrition, Lea & Febiger, Philadelphia.

Hammond, John, 1961, "Growth in Size and Body Proportion in Farm Animals", in Growth in Living Systems, pp. 321-334. Ed. by M. X. Zarrow. Basic Books, Inc., New York.

Heitman Jr., H., C. F. Kelly and T. E. Bond, 1958, "Ambient Air Temperature and Weight Gain in Swine", J. Animal Sci. 17:62-67.

Hogan, G. H., and C. I. Skouby, 1923, "Determination of Surface Area of Cattle and Swine", J. Agr. Research, Vol. 25.

International Business Machines Corp., 1968, "System/360 Continuous System Modeling Program (360A-CX-16X)", User's Manual, Tech. Pub. Dept. White Plains, N. Y.

Ittner, N. R., T. E. Bond and C. F. Kelly, 1958, "Methods of Increasing Beef Production in Hot Climates", Cal. Agr. Exp. Sta. Bull. 761.

Jakob, M., and G. A. Hawkins, 1966, Elements of Heat Transfer, John Wiley and Sons, Inc.

Johnson, A. T., and N. R. Scott, 1969, "A Computer Model of Thermoreceptors", Paper No. 69-435 Presented at 1969 Annual Meeting of Amer. Society of Agr. Engineers, Purdue Univ., W. Lafayette, Indiana.

Johnson, H. D., K. C. Ragsdale and C. S. Cheng, 1957, "Comparisons of the Effects of Environmental Temperatures on Rabbits and Cattle, Part 1", Mo. Agr. Exp. Sta. Res. Bull. 646, Columbia, Mo.

Johnson, H. D., K. C. Ragsdale and C. S. Cheng, 1958, "Comparisons of the Effects of Environmental Temperatures on Rabbits and Cattle Part II", Mo. Agr. Exp. Sta. Res. Bull. 648, Columbia, Mo.

Johnson, H. D., K. C. Ragsdale and R. D. Yeck, 1958, "Effects of Constant Environmental Temperatures of 50 and 80 F on Feed and Water Consumption of Brahman, Santa Gertrudis, and Shorthorn Calves During Growth", Mo. Agr. Exp. Sta. Res. Bull. 683, Columbia, Mo.

Johnson, H. D., and A. C. Ragsdale, 1959, "Effects on Constant Environmental Temperatures of 50 and 80 F on the Growth Responses of Holstein, Brown Swiss, and Jersey Calves", Mo. Agr. Exp. Sta. Res. Bull. 705, Columbia, Mo.

Johnson, H. D., and A. C. Ragsdale, 1960, "Temperature Effects on Thyroid I131 Release Rate of Dairy Calves", Mo. Agr. Exp. Sta. Res. Bull. 709, Columbia, Mo.

Johnson, H. D., Et Al, 1961, "Surface Area Determinations of Beef and Dairy Calves During Growth at 50 and 80 F Environmental Temperatures", Mo. Agr. Exp. Sta. Res. Bull. 770.

Johnson, H. D., Et Al, 1962, "Effect of Various Temperature-Humidity Combinations on Milk Production of Holstein Cattle", Mo. Agr. Exp. Sta. Res. Bull. 791, Columbia, Mo.

Johnson, H. D., Et Al, 1963, "Temperature-Humidity Effects Including Influence of Acclimation in Feed and Water Consumption of Holstein Cattle", Mo. Agr. Exp. Sta. Res. Bull. 846, Columbia, Mo.

Kalmus, H., 1966, Regulation and Control in Living Systems, John Wiley and Sons.

Kamal, T. H., H. D. Johnson and A. C. Ragsdale, 1959, "The Effect of Long Exposure of Environmental Temperatures of 50 and 80 F on Glutathione, BEI 131, and Growth Rate of Dairy Calves", Mo. Agr. Exp. Sta. Res. Bull. 710, Columbia, Mo.

Kennedy, G. C., 1966, "Food Intake, Energy Balance and Growth", Brit. Med. Bull. 22:216-220.

Kibler, H. H., and S. Brody, 1952, "Relative Efficiency of Surface Evaporative, Respiratory Evaporative, and Non-Evaporative Cooling in Relation to Heat Production in Jersey, Holstein, Brown Swiss and Brahman Cattle, 5 to 105 F", Mo. Agr. Exp. Sta. Res. Bull. 497, Columbia, Mo.

Kibler, H. H., and S. Brody, 1950, "Effects of Temperature, 50 to 105 F and 50 to 9 F on Heat Production and Cardiorespiratory Activities in Brahman, Jersey and Holstein Cows", Mo. Ag. Exp. Sta. Res. Bull. 464, Columbia Mo.

Kibler, H. H., and S. Brody, 1954, "Influence of Wind on Heat Exchange and Body Temperature Regulation in Jersey, Holstein, Brown Swiss, and Brahman Cattle", Mo. Ag. Exp. Sta. Res. Bull. 552, Columbia, Mo.

Kibler, H. H., and S. Brody, 1954, "Influence of Radiation Intensity on Evaporative Cooling, Heat Production, and Cardiorespiratory Activities in Jersey, Holstein, and Brahman Cows", Mo. Agr. Exp. Sta. Res. Bull. 574, Columbia, Mo.

Kibler, H. H., 1957, "Energy Metabolism and Cardiorespiratory Activities in Shorthorn, Santa Gertrudis, and Brahman Heifers During Growth at 50 and 80 Degrees F Temperature", Mo. Agr. Exp. Sta. Res. Bull. 643, Columbia, Mo.

Kibler, H. H., and R. D. Yeck, 1959, "Vaporization Rates and Heat Tolerance in Growing Shorthorn, Brahman, and Santa Gertrudis Calves Raised at Constant 50 and 80 F Temperatures", Mo. Agr. Exp. Sta. Res. Bull. 701, Columbia, Mo.

Kibler, H. H., 1960, "Energy Metabolism and Related Thermoregulatory Reactions in Brown Swiss, Holstein, and Jersey Calves During Growth at 50 and 80 F Temperatures", Mo. Agr. Exp. Sta. Res. Bull. 743, Columbia, Mo.

Kiesling, H. E., 1971, Personal Communication, Oklahoma State University.

Kleiber, M., 1961, The Fire of Life, An Introduction to Animal Energenics,Wiley, New York.

Korn, G. A., and T. M. Korn, 1964, Electronic Analog and Hybrid Computers, McGraw-Hill, Inc.

Koenig, H. E., Et Al, 1967, Analysis of Discrete Physical Systems, McGraw-Hill, Inc.

Lehninger, A. L., 1970, Biochemistry, The Molecular Basis of Cell Structure and Function, Worth Publishers, Inc., N. Y.

Leondes, C. T. (Ed), 1961, *Computer Control Systems Technology*, McGraw-Hill, Inc.

Link, D. A., and W. E. Splinter, 1968, "Survey of Simulation Techniques and Applications to Agricultural Problems", Paper Presented at 1968 Summer Meeting of *Amer. Society of Agr. Eng.*, Logan, Utah.

Lofgreen, G. P., and W. N. Garrett, 1967, "Net Energy Requirements and Feed Values for Growing and Finishing Cattle", Paper Presented at the *Calif. Cattle Feeders Annual Meeting*.

Lofgreen, G. P., and W. N. Garrett, 1968, "A System for Expressing Net Energy Requirements and Feed Values for Growing and Finishing Beef Cattle", *J. Animal Science*, Vol. 27, pp. 793-806.

Mason Jr., J. P., M. D. Shanklin and R. E. Stewart, 1965, "Homeothermic Regulation Quantitatively Analogized to a Closed-Loop System", Trans. *Amer. Society of Agricultural Engineering*, Vol. 8, No. 4, pp. 476-480.

Maynard, L. A., and J. K. Loosli, 1969, *Animal Nutrition* (6th Ed) McGraw-Hill Co.

McCollum, P. A., 1968, "Analog and Hybrid Computers", Class Notes-Elen 6213, Oklahoma State University.

McMeekan, C. P., 1940, "Growth and Development in the Pig with Special Reference to Carcass Quality Charater", Part I, II, III, *J. Agr. Science*, Vol. 30, 1940, Part IV, V, *J. Agr. Science*, Vol. 31, 1941.

Medawar, P. B., 1945, "Size, Shape, and Age", in *Essays on Growth and Form*, Clark and Medawar, The Clarendon Press, Oxford, England.

Mesarovic, M. D., 1968, "Systems Theory and Biology", *Proceedings of the III Systems Symposium at the Case Institute of Technology*, Springer-Verlag, New York.

Milhorn Jr., H. T., 1966, *The Application of Control Theory To Physiological Systems*, W. B. Saunders Co., Philadelphia.

Milsum, J. H., 1966, *Biological Control System Analysis*, McGraw-Hill Inc., New York.

Montgomery, M. J., and B. R. Baumgardt, 1965, "Regulation of Food Intake in Ruminants. 2. Rations Varying in Energy Concentration and Physical Form", *J. Dairy Sci.*, 48:1623-1628.

Morrison, F. B., 1956, *Feeds and Feeding*, 22nd Ed., Morrison Publishing Co., Ithaca, New York.

Murphy, G. J., 1966, *Basic Automatic Control Theory*, D. Van Nostrand Co., Inc., Princeton, N. J.

Needham, A. E., 1969, *The Growth Process in Animals*, D. Van Nostrand Co., Inc., Princeton, N. J.

Nixon, F. E., 1953, *Principles of Automatic Controls*, Prentice-Hall Inc., Englewood Cliffs, N. J.

Ogata, K., 1967, *State Space Analysis of Control Systems*, Prentice-Hall Inc., Englewood Cliffs, N. J.

Parker, J. D., J. H. Boggs and E. F. Blick, 1969, *Introduction to Fluid Mechanics and Heat Transfer*, Addison Wesley Publishing Co., Inc.

Parpart, A. K. (Ed.), 1949, *The Chemistry and Physiology of Growth*, Princeton University Press, Princeton, N. J.

Pedersen, L., 1969, "The Heat Regulation of the Human Body", *Acta Physiol. Scand.* 77. 95-105.

P'alsson, H., 1955, "Conformation and Body Composition", in *Progress in Physiology of Farm Animals*, Hammond H. Ed. Vol. 2, London.

P'alsson, H., and J. B. Verges, 1952, "Effects of the Plane of Nutrition on Growth and the Development of Carcass Quality in Lambs, I: The Effect of High and Low Planes of Nutrition at Different Ages", *J. Agr. Sci.* 42, 1.

Ragsdale, A. C., Et Al, 1948, "Influence of Temperature, 50 to 105 F, on Milk Production and Feed Consumption in Dairy Cattle", *Mo. Ag. Exp. Sta. Res. Bull.* 425, Columbia, Mo.

Ragsdale, A. C., Et Al, 1951, "Influence of Increasing of Temperature 40 to 105 F on Milk Production in Brown Swiss Cows, and on Feed and Water Consumption and Body Weight in Brown Swiss and Brahman Cows and Heifers", *Mo. Ag. Exp. Sta. Res. Bull.* 471, Columbia, Mo.

Ragsdale, K. C., C. S. Cheng and H. D. Johnson, 1957, "Effects of Constant Environmental Temperatures of 50 Degrees F and 80 Degrees F on the Growth Response of Brahman, Santa Gertrudis, and Shorthorn Calves", *Mo. Agr. Exp. Sta. Res. Bull.* 642, Columbia, Mo.

Reid, J. T., Et Al, 1968, "Some Peculiarities in Body Composition of Animals", in *Body Composition in Animals and Man*, Pub 1598 National Academy of Sciences, Wash. D. C.

Reine, J. M., 1968, *The Organism as an Adaptive Control System*, Prentice Hall, Englewood Cliffs, N. J.

Schneider, B. H., 1947, *Feeds of the World*, Jarret Printing Co., W. Va.

Schwarz, R. J., and B. Friedland, 1965, *Linear Systems*, McGraw-Hill, Inc.

Sebesta, H. R., 1969, "Automatic Control I", (Class Notes-Mechen 5473) Oklahoma State University.

Shanklin, M. D., and R. E. Stewart, 1958, "Relief of Thermally-Induced Stress in Dairy Cattle by Radiation Cooling", *Mo. Agr. Exp. Sta. Res. Bull.* 670, Columbia, Mo.

Simkins Jr., K. L., J. W. Suttie and B. R. Baumgardt, 1965, *J. Dairy Sci.* 48:1629.

Singh, R., and C. P. Merilan, 1957, "Influence of Temperature on Vitamin Levels in Bovine Blood," *Mo. Ag. Exp. Sta. Res. Bull.* 639, Columbia, Mo.

Spillman, C. K., and C. N. Hinkle, 1969, "Conduction Heat Transfer from Swine to Controlled Temperature Floors", Paper 69-441, *Amer. Society of Agr. Eng.*, Purdue Univ., Lafayette, Indiana.

Stear, E. B., and A. H. Kadish (Ed.), 1969, *Hormonal Control Systems*, Proceeding of Symposium, Oct. 20-22, 1967 at Rancho Santa Fe, California, American Elsevier Pub. Co., Inc., N. Y.

Stewart, R. E., and M. D. Shanklin, 1958, "Effects of Growth and Environmental Temperature on Surface Temperatures of Beef Calves", *Mo. Agr. Exp. Sta. Res. Bull.* 656, Columbia, Mo.

Taylor, C. S., and G. B. Young, 1964, "Variation in Growth and Efficiency in Twin Calves", *J. Agr. Science*, Vol. 62.

Taylor, C. S., and G. B. Young, 1966, "Variation in Growth and Efficiency in Twin Cattle with Live Weight and Food Intake Controlled", *J. Agr. Science*, Vol. 66.

Wagner, D. G., and J. K. Loosli, 1967, "Studies on the Energy Requirements of High Producing Dairy Cows", *Cornell Univ. Agr. Exp. Sta. Memoir*, 400:1-40.

Wiersma, F., 1966, "A Model for Predicting Non-Evaporative Convective Heat Loss for the Surface of a Bovine", Ph.D. Thesis, Oklahoma State University.

Witz, J. A., 1971, Personal Communication and Ph.D. Thesis, Oklahoma State University.

Yamamoto, W. S., and J. R. Brobeck (Eds.), 1965, *Physiological Controls and Regulations*, W. B. Saunders Co., Philadelphia.

Yates, F. E., Et Al, 1968, "A Continuous System Model of Adrenocortical Function", in *Systems Theory and Biology*, Mesarovic (Ed), Springer-Verlag, Inc., New York.

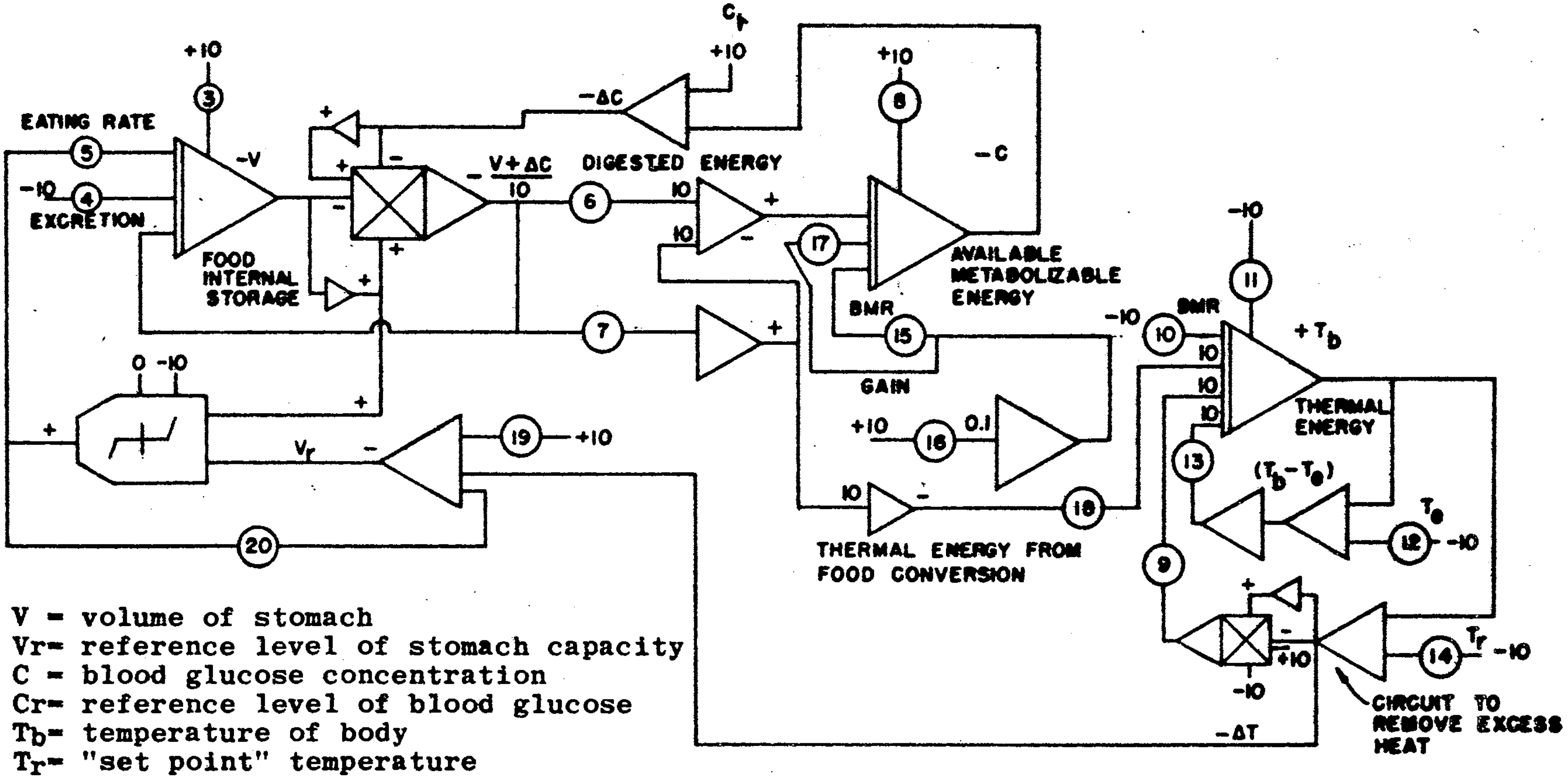
Yeck, R. D., 1957, "Stable Heat and Moisture Dissipation with Beef Calves at Temperatures of 50 and 80 Degrees F", _Mo_. _Agr_. _Exp_. _Sta_. _Res_. _Bull_. 645, Columbia, Mo.

APPENDICES

APPENDIX A

ANALOG CIRCUIT AND OUTPUT CURVES FOR KLEIBER'S CONCEPT

ANALOG CIRCUIT TO ILLUSTRATE CONCEPTUAL MODEL OF ENERGY FLOW WITHIN AN ANIMAL



V = volume of stomach
Vr = reference level of stomach capacity
C = blood glucose concentration
Cr = reference level of blood glucose
Tb = temperature of body
Tr = "set point" temperature
Te = temperature of environment

Figure 40. Analog circuit to illustrate conceptual model for energy flow within an animal.

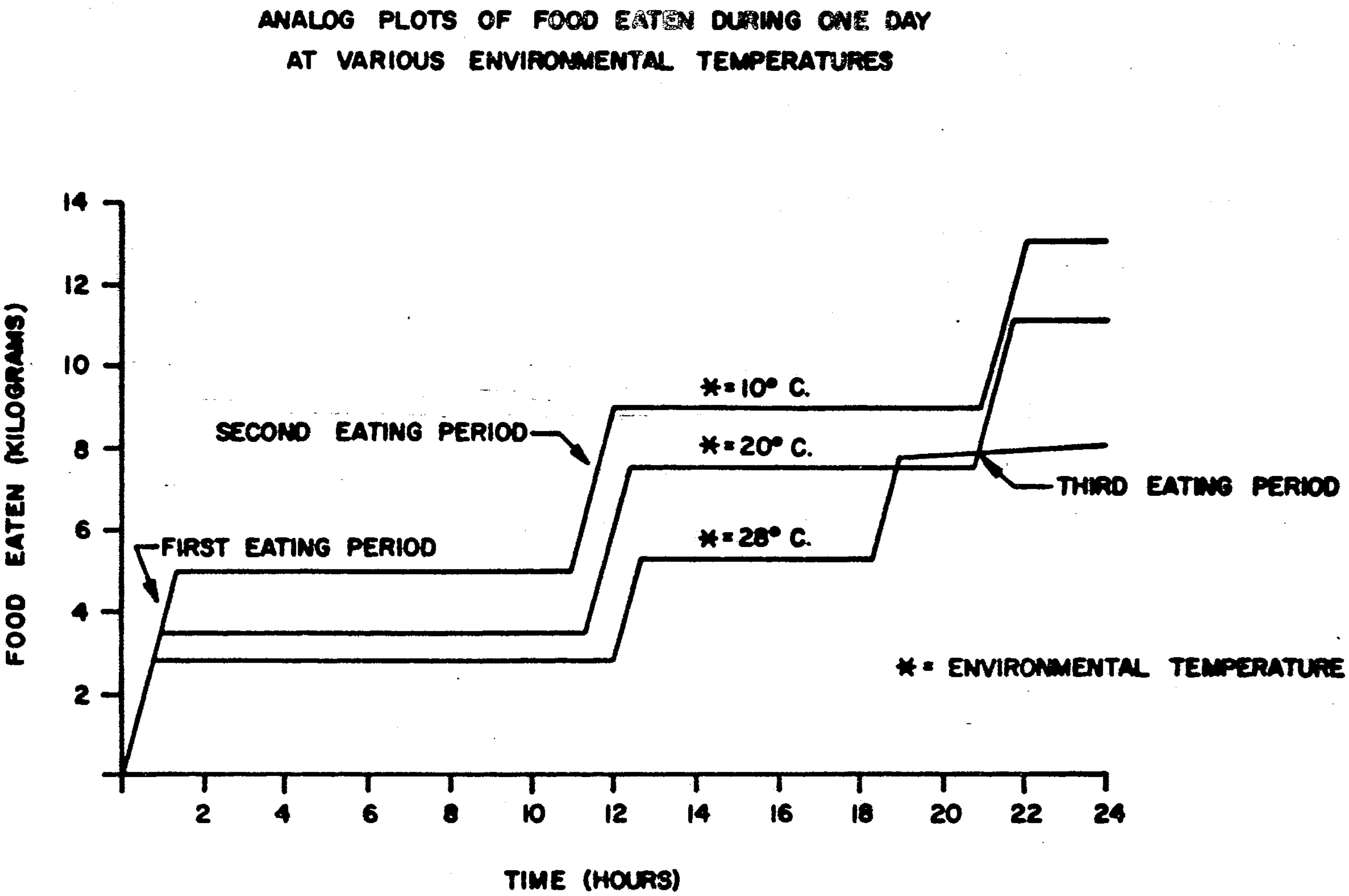


Figure 41. Analog plots of food eaten during one day. Curves represent accumulation of total weight of food consumed each day.

APPENDIX B

SCHEMATIC DIAGRAMS AND CSMP LISTINGS FOR GROWTH SECTION

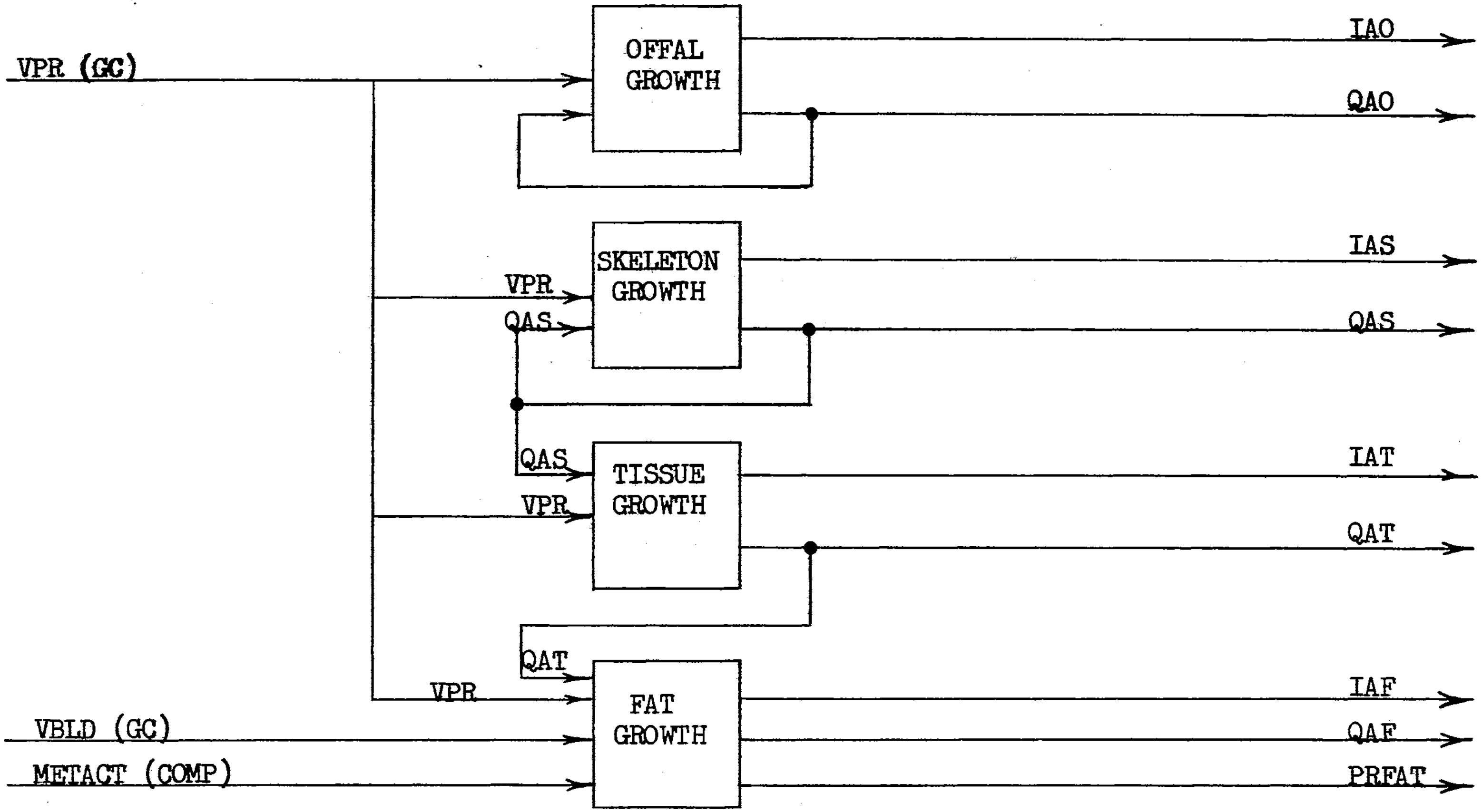


Figure 42. Major flow chart for growth section showing forcing functions and major interconnections between component growth modules.

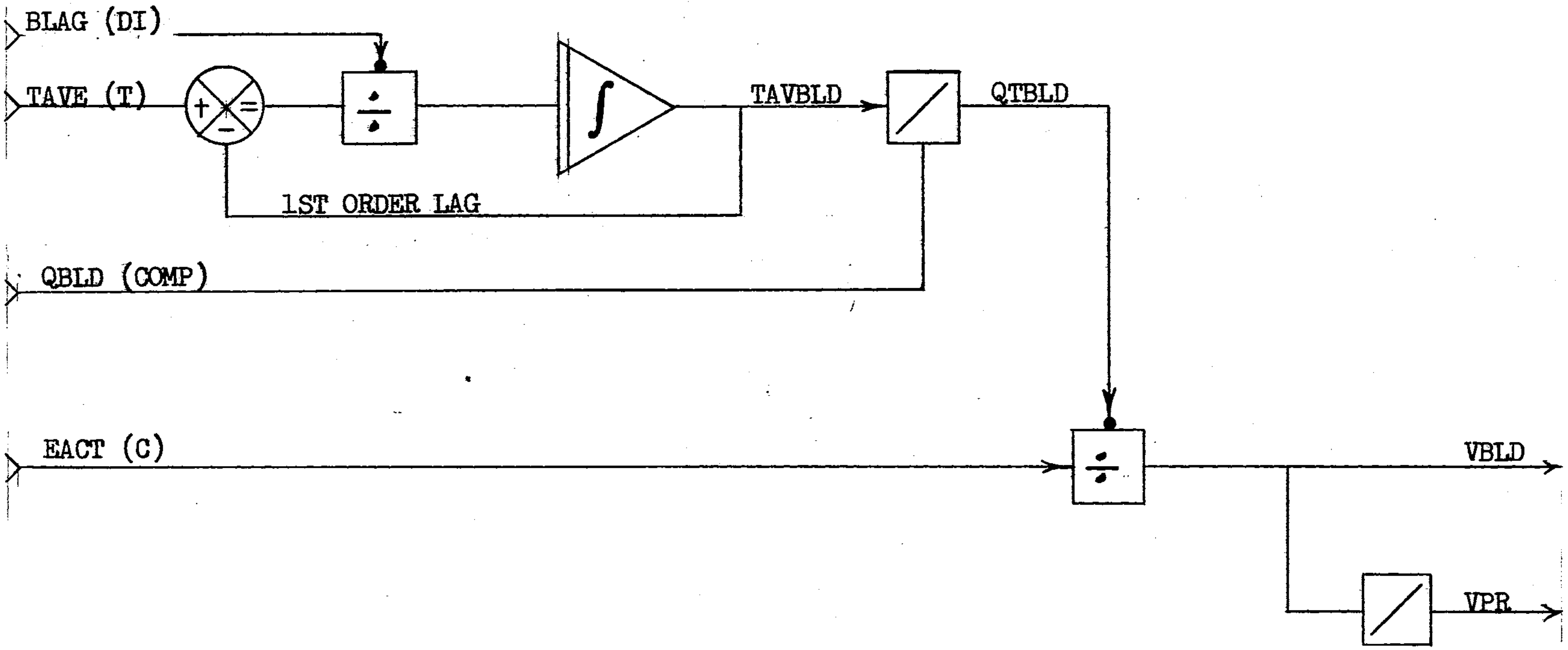


Figure 43. Module schematic for growth control, illustrating the change in blood volume as a function of temperature.

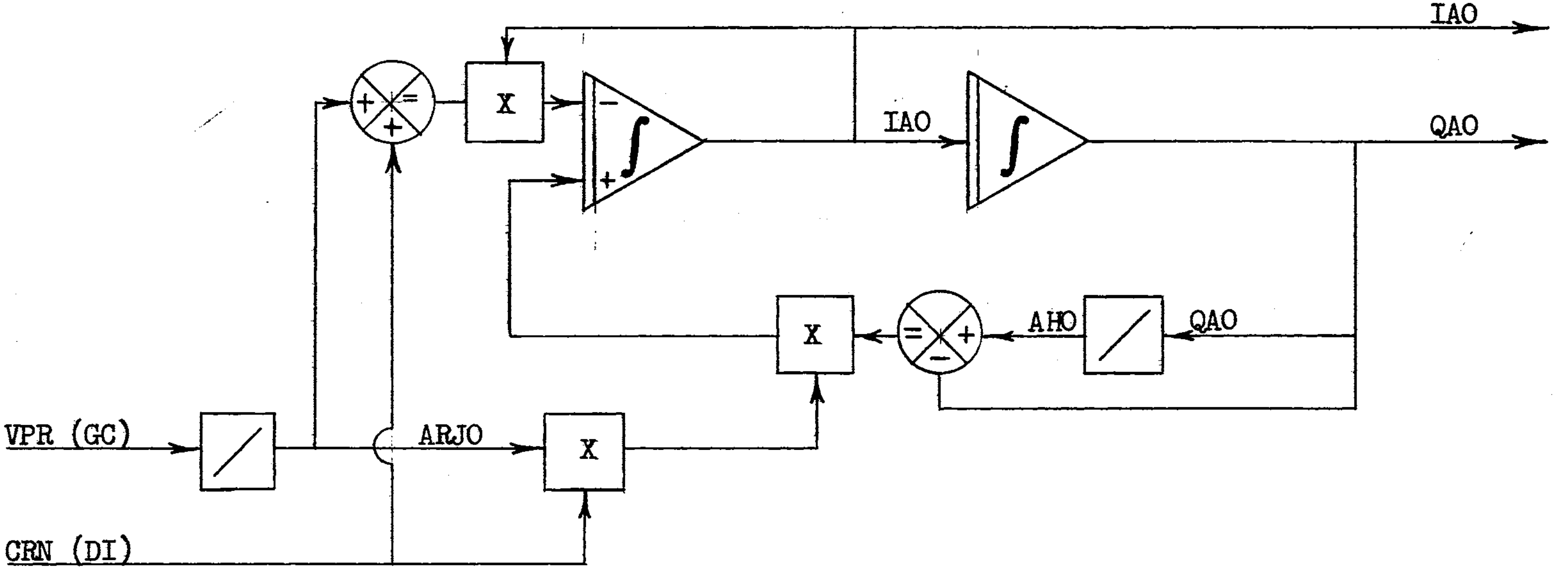


Figure 44. Detailed module schematic for growth of offal in a beef animal.

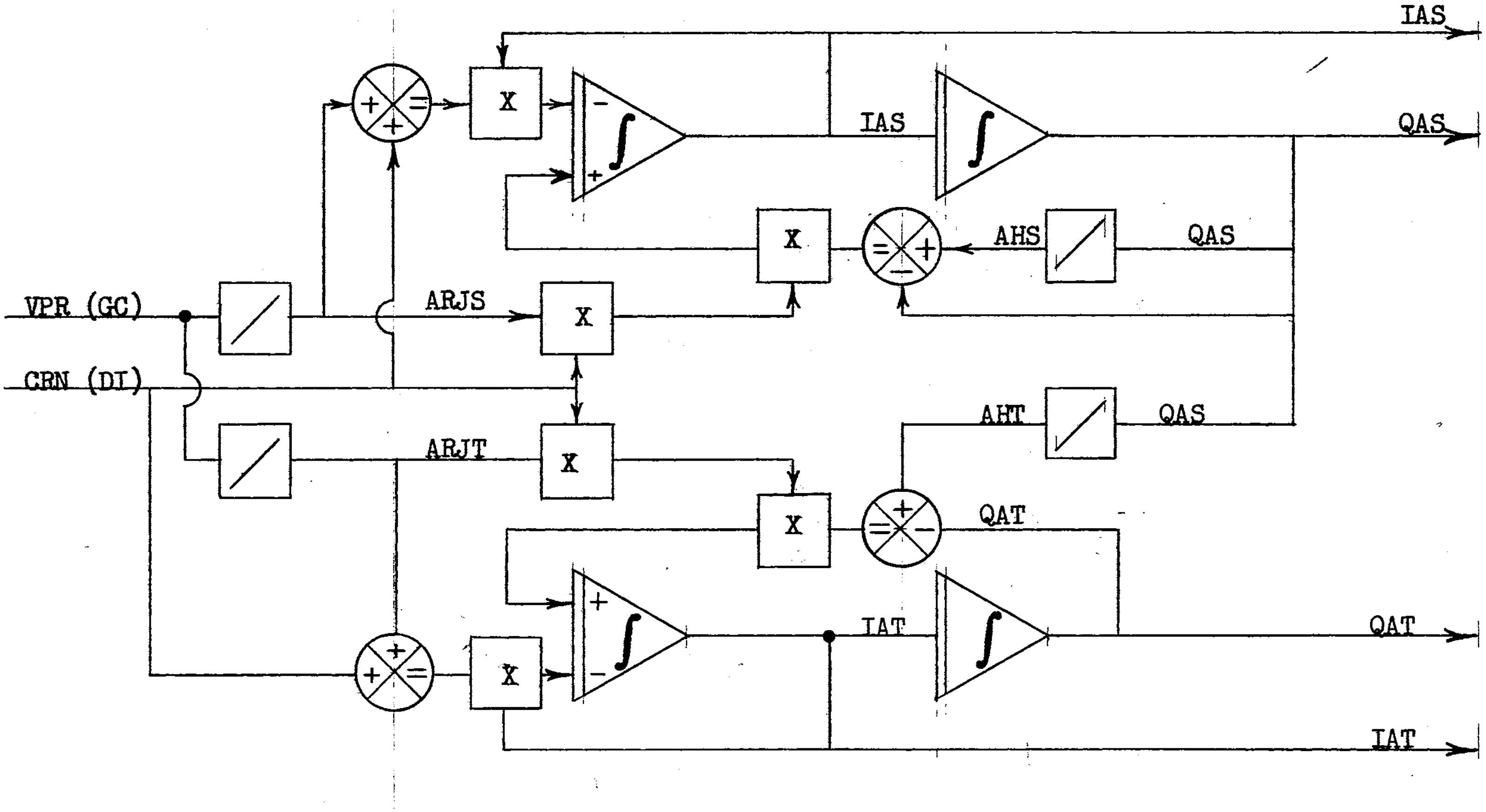


Figure 45. Detailed module schematic for growth of skeleton and meat tissue in a beef animal.

```
******     GROWTH CONTROL, OFFAL, SKELETON, AND TISSUE GROWTH            *********

       INCON TAVEO=37.22
       INCON SIAO=0.0079,   SQAO=106.0
      INCON SIAS=0.00172,  SQAS=26.0
       INCON SIAT=0.0068,   SQAT= 78.0
       CONSTANT BLAG=48.0,            CNBLDA=-4.6, CNBLDB=0.15
       CONSTANT CORVPR=-0.02149
       CONSTANT CNVPR=0.0245388
       CONSTANT CRN=2.0
       CONSTANT CROA=0.0
       CONST CHOO=84.1534,CHOD=.770092
       CONST CROO=.24965E-04,CROD=.51845E-03
       CONSTANT CRSA=0.0
       CONSTANT CRTA=0.0
       CONST CHSO=21.29,CHSD=.6581
       CONST CRSO=-.1822E-07,CRSD=.6767E-03
       CONST CHTO=102.6,CHTD=1.623
       CONST CRTO=-.1746E-09,CRTD=.5000E-03

DYNAMIC
******   COMPUTATION OF ACETATE POWER/BLOOD WEIGHT RATIO                 M---
         TAVBX=(TAVE-TAVBLD) /BLAG
       TAVBLD=INTGRL(TAVEO,TAVBX)
       MBLDV=CNBLDA+CNBLDB*TAVBLD
       QTBLD=MBLDV*QBLD
       VBLD=EACT/QTBLD
       VPR=CNVPR*VBLD-CCRVPR

******   OFFAL GROWTH                                                    *********
       AHO=CHOO+CHOD*QAO
       ARJO=CROO +VPR*(CROD+VPR*CROA)
       AFO=CRN*(AHO-QAO)
       DIAO=ARJO*AFO-(CRN+ARJO)*IAO
       IAO=INTGRL(SIAO,DIAO)
       QAO=INTGRL(SQAO,IAO)

******   SKELETON GROWTH                                                 *********
       AHS=CHSO+CHSD*QAS
       ARJS=CRSO +VPR*(CRSD+VPR*CRSA)
       AFS=CRN*(AHS-QAS)
       DIAS=ARJS*AFS-(CRN+ARJS)*IAS
       IAS=INTGRL(SIAS,DIAS)
       QAS=INTGRL(SQAS,IAS)

******   TISSUE GROWTH                                                   *********
       AHT=CHTO+CHTD*QAS
       ARJT=CRTO +VPR*(CRTD+VPR*CRTA)
       AFT=CRN*(AHT-QAT)
       DIAT=ARJT*AFT-(CRN+ARJT)*IAT
       IAT=INTGRL(SIAT,DIAT)
       QAT=INTGRL(SQAT,IAT)
```

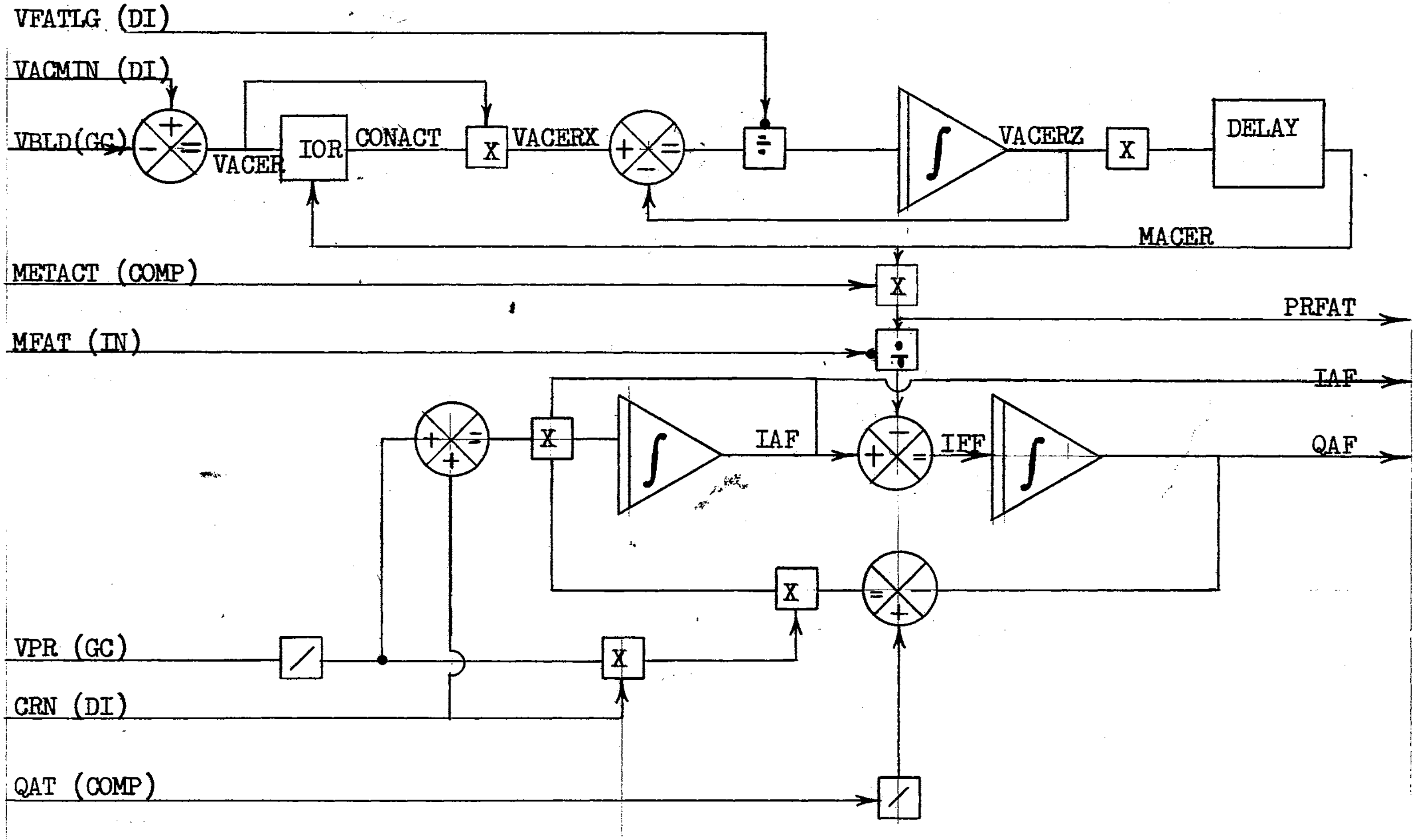


Figure 46. Detailed module schematic for fat growth and fat catabolism in a beef animal.

```
******                          FAT GROWTH                                ********
      INCON VACO=0.0
      INCON SIAF=0.0037,   SQAF=43.4

      CONSTANT VACERX =0.0
      CONSTANT LFAT=1.0
      CONSTANT CNFATQ=9400.0
      CONSTANT P=0.01
      CONSTANT CNACFT=1.0
      CONSTANT VACMIN=2.0,VFATLG=0.25
      CONSTANT CITO = 1.E-30
      CONSTANT CRN=2.0
      CONSTANT CRFA=0.0
      CONST CRFO=-.3622E-04,CRFD=.48432E-03
      CONST CHFO=-89.27,CHFD=2.4528

INITIAL

      MFAT=(1.0       )/CNFATQ

DYNAMIC

******   POWER FROM FAT BASED UPON MINIMUM ACETATE CONCENTRATION         ********

PROCEDURE PRFAT=FATXX(VBLD,VACMIN,VACO,VFATLG,CNACFT,METACT)
      IF(LFAT)832,832,831
  831 VACER=VACMIN-VBLD
      CONACT=0.0
      IF(VACER.GT.0.0) CONACT=1.0
      IF(MACER.GT.0.0) CONACT=1.0
      VACERX=CONACT*VACER
      VFATX= (VACERX-VACERZ)/VFATLG
      VACERZ=INTGRL(VACO,VFATX)
      IF (VACERZ.LT.CITO)VACERZ=0.0
      MACERX=CNACFT*VACERZ-CITX
      MACER=DELAY(1,P,MACERX)
      PRFAT=METACT*MACER
  832 CONTINUE
ENDPRO

******   FAT GROWTH                                                        ********

      AHF=CHFO+CHFD*QAT
      ARJF=CRFO +VPR*(CRFD+VPR*CRFA)
      AFF=CRN*(AHF-QAF)
      DIAF=ARJF*AFF-(CRN+ARJF)*IAF
      IAF=INTGRL(SIAF,DIAF)
      IFF=IAF-PRFAT*MFAT
      QAF=INTGRL(SQAF,IFF)
```

APPENDIX C

VERIFICATION OF STANDARD CURVES

The data reported by Kibler, 1957, was shown in a scattergraph on logarithmic scales. To achieve a fit of the equation $Y = aW^b$, Kibler divided the data into two sections and determined constants and coefficients for each section of data.

The original data was deciphered from the scattergraphs and a polynomial equation was used to fit the data. As shown in Figure 47 the polynomial equation was a better fit of the data than the exponential curves reported.

The curves for the areas of the Shorthorn animals are plotted in Figure 48 along with curves calculated from Brody's equation and the equation reported by Johnson, 1961. Because neither Brody's or Johnson's equation fit the data accurately, a fifth order polynomial equation was developed to reproduce the empirical surface area below animal weights of 375 kg.

The coefficients and exponents reported by Ragsdale, Cheng, and Johnson, 1957, for the exponential curves relating weight to time were checked against the original data. There appeared to be very little variation of the data from the predicted weight as a function of time. Therefore, the equations and their coefficients and exponents as reported were used for the standard equation for growth comparisons.

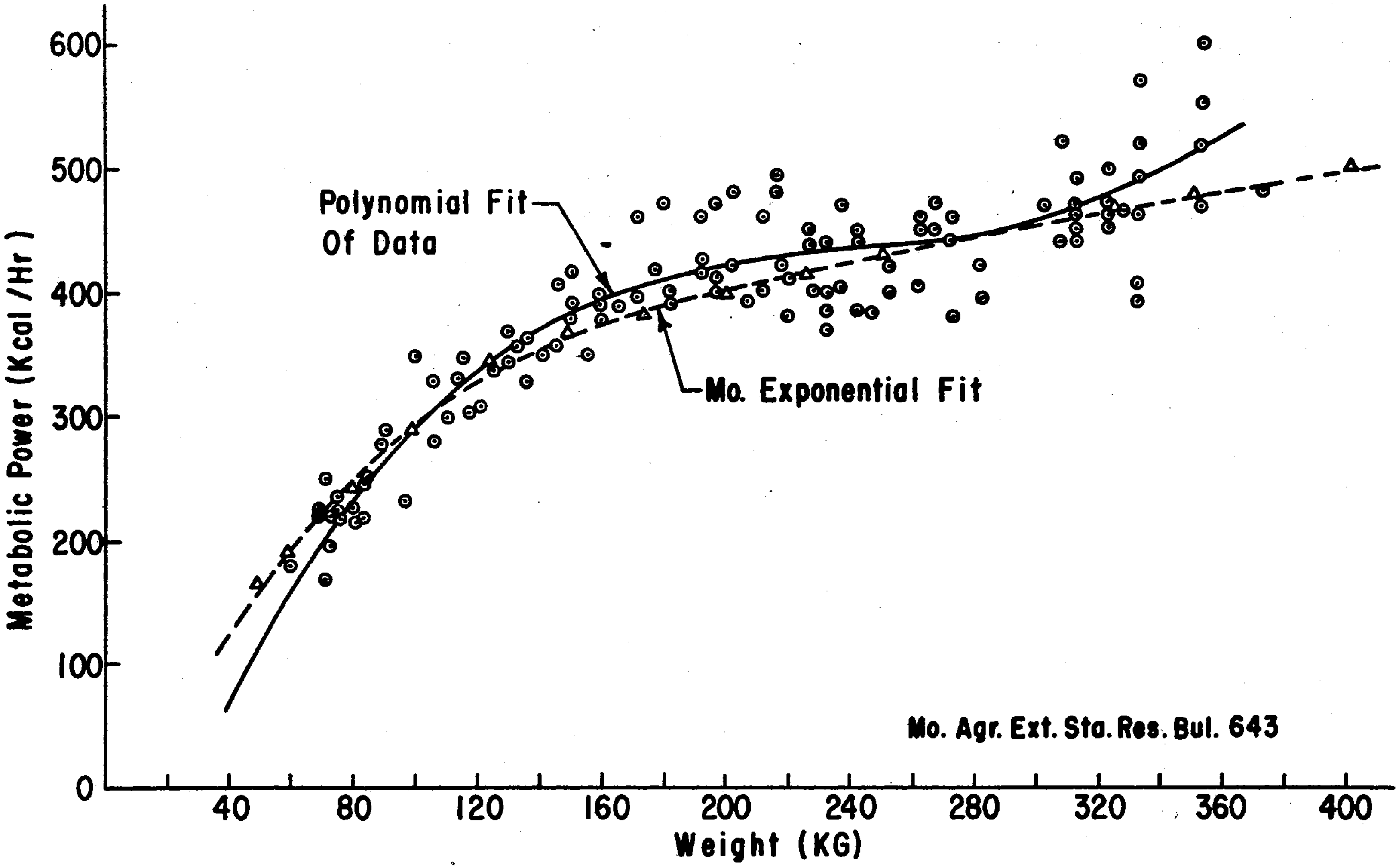


Figure 47. A polynomial fit of the original data compared to the reported exponential fit.

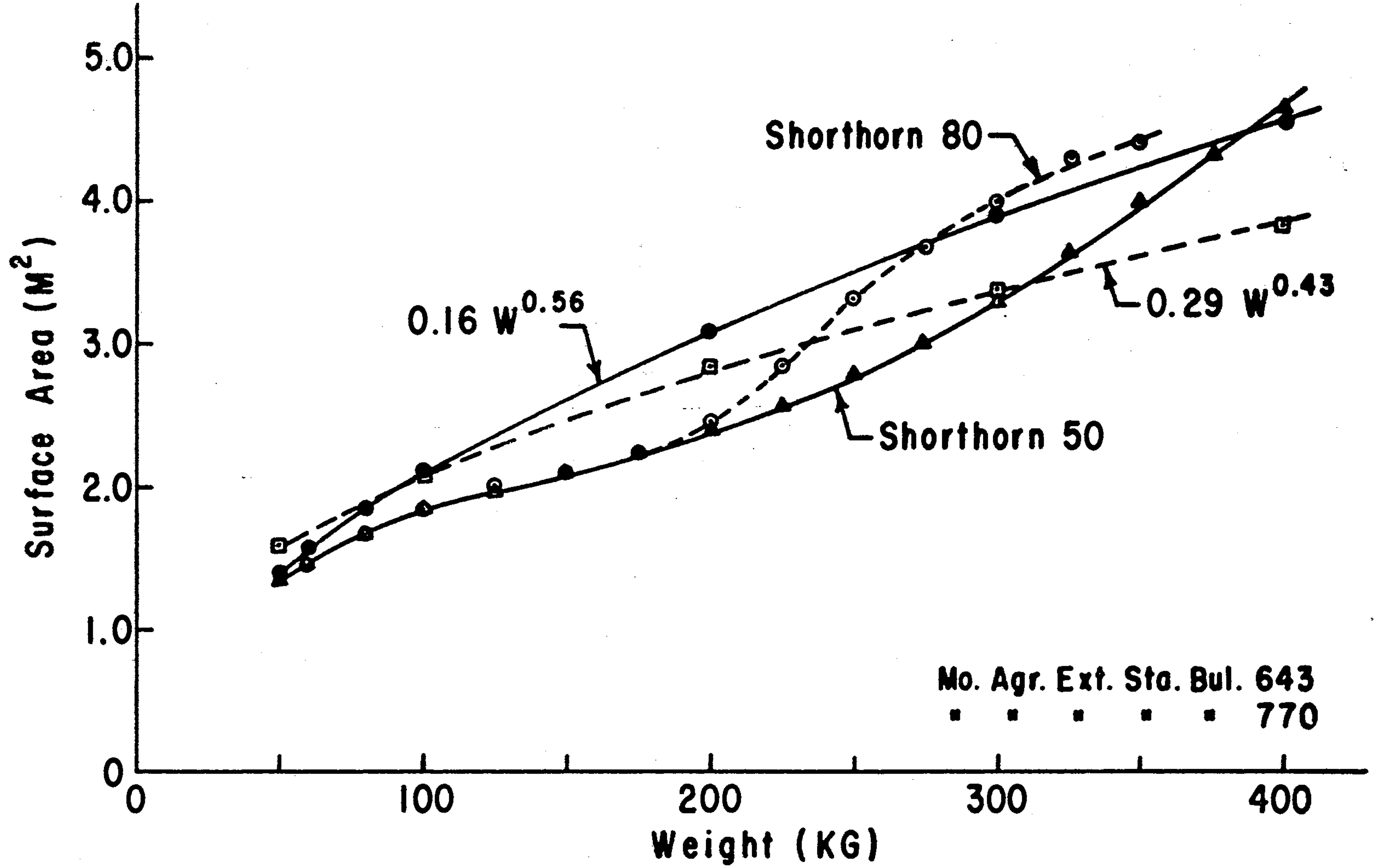


Figure 48. Exponential predictions of surface area compared to reported data.

APPENDIX D

COMPUTER PROGRAM TO DETERMINE HEAT TRANSFER COEFFICIENTS

```
;
/*     Program to determine composition and heat         */;
/*     transfer coefficients for equivalent cylinder     */;
;
DECLARE w(66)  DEC(6), tb(66)  DEC(6), ts(66)  DEC(6);
DECLARE th(66)  DEC(6);
DO i=1 TO 66;
IF ts(i)=0 THEN GO TO fin;
;
/*     Establish empirical relationships for skin        */;
/*     and respiratory vapor, area and ventilation rate */;
;
rv=-20.548753+.719098*w(i)-.00452536*w(i)*w(i);
rv=rv+.0000116958*w(i)**3-.0000000110609*w(i)**4;
sv=23.068873+.132755*w(i)-.00131321*w(i)*w(i);
sv=sv+.0000408629*w(i)**3-.428488E-08*w(i)**4;
area=.3619967+.0264629*w(i)-.0001632319*w(i)*w(i);
area=area+.0000005070253*w(i)**3-.49167727E-09*w(i)**4;
vent=18.562-.94888*w(i)+.019985*w(i)*w(i);
vent=vent-.00016172*w(i)**3+.00000064098*w(i)**4;
vent=vent-.12344E-08*w(i)**5+.92738E-12*w(i)**6;
vent=vent/20;
;
/*     Compute percent of body components                 */;
;
pfat=xfat*w(i);
pgi=gia*w(i)**gib;
IF w(i)<176 THEN pgi=.4*w(i);
IF w(i)<101 THEN pgi=.3*w(i);
dgi=pgi/(pgi+3*vent);
pgi=pgi/w(i);
pmus=pflh-pfat-pgi;
den=pfat*dfat+pmus*dmus+pgi*dgi+pbone*dbone;
;
/*     Compute radii of component rings                   */;
;
```

```
rs=w(i)*1000*2/(area*10000*den);
rs=rs/100;
L=area/(2*pi*rs);
dt=tb(i)-ts(i);
rf=rs-skin;
csa=pi*rf*rf;
rm=((csa-pfat*csa/dfat)/pi)**.5;
rb=((pi*rm*rm-pmus*csa/dmus)/pi)**.5;
rg=((pi*rb*rb-pbone*csa/dbone)/pi)**.5;
rh=rs+hair;
;
/*     Compute Physical properties for themal transfer   */;
;
ds=(rh+rs)/2;
df=(rs+rf)/2;
dm=(rf+rm)/2;
db=(rm+rb)/2;
dg=(rb+rg)/2;
ls=LOG(ds/df);
lf=LOG(df/dm);
lm=LOG(dm/db);
lb=LOG(db/dg);
lg=LOG(dg/(rg/2));
cag=pi*rg*rg;
cab=pi*(rb*rb-rg*rg);
cam=pi*(rm*rm-rb*rb);
caf=pi*(rf*rf-rm*rm);
cas=pi*(rs*rs-rf*rf);
;
/*     Compute power distribution per unit area          */;
;
q=qa+w(i)*(qb+w(i)*(qc+w(i)*(qd+w(i)*qe)));
qpa=q/area;
qpv=q*den/w(i);
q=qpv/.001;
q=q*(csa+cas)/(cag+.1*cab+cam+.2*caf+cas);
```

```
        k=1;
        qr=rv*2*rs/(rg*rg);
        qs=sv*2*rs;
        ;
        /*     Compute heat transfer coefficients                    */;
        ;
        knt=0;
again:  tgb=(q-qr)*rg*rg*lg/(2*k);
        tbm=.1*q*(rb*rb-rg*rg)+2*k*tgb/lg;
        tbm=tbm*lb/(2*k);
        tmf=q*(rm*rm-rb*rb)+2*k*tbm/lb;
        tmf=tmf*lm/(2*k);
        tfs=.2*q*(rf*rf-rm*rm)+2*k*tmf/lm;
        tfs=tfs*lf/(2*k);
        tot=tgb+tbm+tmf+tfs;
        IF knt=1 THEN GO TO cont;
        knt=1;
        k=k*tot/dt;
        GO TO again;
cont:   dth=ts(i)-th(i);
        dte=th(i)-10;
        kh=1;
        H=1;
        knt=0;
again2: tsh=q*(rs*rs-rf*rf)+2*k*tfs/lf-qs;
        tsh=tsh*ls/(2*kh);
        IF knt=1 THEN GO TO cont2;
        knt=1;
        kh=kh*tsh/dth;
        GO TO again2;
cont2:  knt=0;
again3: the=2*tsh*kh/(ls*2*rh*H);
        IF knt=1 THEN GO TO cont3;
        knt=1;
        H=H*the/dte;
        GO TO again3;
```

```
                ;
                /*      Compute power out and temperatures, Print         */;
                ;
       cont3:   TS=ts(I);
                qout=qpa-rv;
                qhout=qpa-rv-sv;
                TH=TS-tsh;
                TF=TS+tfs;
                TM=TF+tmf;
                TB=TM+tbm;
                TG=TB+tgb;
                resh=ls/(2*kh);
                TAVE=TG*cag+TB*.1*cab+TM*cam;
                TAVE=TAVE/(cag+cam+.1*cab);
                PUT IMAGE(I,w(I),area,qout,qhout,TG,TH,TAVE,k,kh,H)(f);
       f:       IMAGE;
-- ---  ---.---  ---.---  ---.---  ---.---  ---.---  ---.---  ---.---  --.---  ---.---
       fin:     END ;
                END ;
```

APPENDIX E

RADIATION CALCULATION PROCEDURE

The Missouri calves were stanchioned side by side in groups of three within pens having aluminum sides and back wall. To be able to estimate the grey body radiation from the animals, a rectangular body was assumed with a configuration as shown in Figure 49. The dimensions used were determined from the pen information reported in the Missouri bulletins 643 and 645, and from typical dimensions of animals weighing 375 kg, as reported by Brody, 1945.

The summary work sheet of the calculations is shown in Table XI. Two animals were located near an aluminum side wall, while one animal was in the middle. Two environmental temperatures are used because the reported data indicated that the bedding temperature averaged slightly higher than the environment. The ceiling was assumed to be warmer also.

The average view factor for each area was estimated by determining the view factor for small elements in the corners, and sides, of the rectangle and then averaging them. The elemental view factors were determined from charts in Parker, Boggs, and Blick, 1969.

The heat transferred, between each animal area and the environmental areas associated with it, was calculated. A combined estimate of grey body radiation was made for a three animal pen. The resultant value was divided by a weighted average estimate of black body

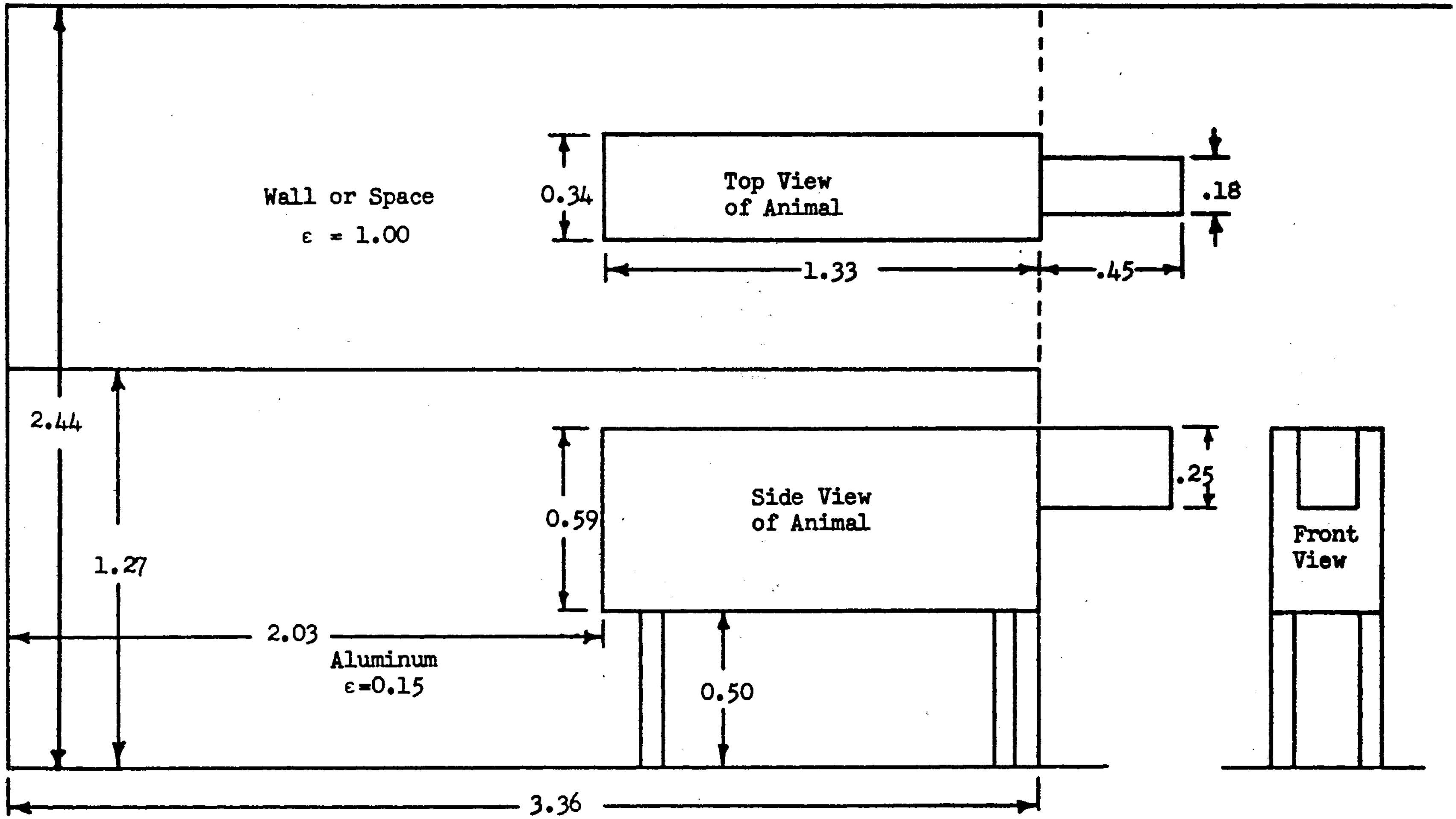


Figure 49. Room configuration used for radiation calculation purposes.

TABLE XI

RADIATION CALCULATIONS

Animal	Side	View	AREAS		E View	Temp View (oC)	F	Q View Kcal/hr	Q Side Kcal/hr	Mult
			Animal (M^2)	View (M^2)						
Near & Far	N.Side	Parll.	0.8597	0.8597	0.15	11.7	0.48	6.61		
		Al Wall	"	3.4075	"	"	0.25	9.42		
		Wall	"	20	0.95	"	0.27	13.76	29.79	2
	F.Side	Parll.	—	—	—	—	.48	0		
		Wall	0.8597	20	0.95	"	.52	26.29	26.29	2
	F.Head	Wall	0.1125	20	0.95	"	1.0		6.53	6
	Rear	Al Side	0.2756	2.5781	0.15	"	0.24	3.43		
		Al Wall	"	3.048	0.15	"	0.12	1.86		
		Wall	"	20	0.95	"	0.64	10.34	15.63	2
	Front	Stnchn	0.2756	0.254	0.25	"	0.25	2.26		
		Wall	"	20	0.95	"	0.75	12.08	14.34	3
	Bttm	Al Wall	0.5332	.665	0.15	"	0.21	3.42		
		Floor	"	20	0.95	13.4	0.79	21.36	24.78	3
Middle	Side	Parll.	—	—	—	—	.48	0		
		Al Wall	.8597	3.042	0.15	11.7	0.10	4.42		
		Wall	"	20	0.95	11.7	0.42	21.31	25.73	2
	Rear	Al Side	0.2756	5.1562	0.15	11.7	0.34	5.03		
		Al Wall	"	3.048	0.15	"	0.18	2.70		
		Wall	"	20	0.95	"	0.48	7.80	15.53	1
	Top	Ceiling	0.5332	20	0.95	13.4	1.0		26.86	3

Animal Area 3.562

Radiation Total = 447.53

Radiant Power/Area = 41.88 $\frac{Kcal}{M^2}$

radiation. The answer was assumed to be the percent of theoretical black body radiation actually transmitted from the animal's surface.

Weighted Average Black Body Radiation/Animal,
2.4956 * 59.83 = 149.3117
1.0664 * 52.00 = 55.4528
204.7645 Kcal
*3
614.28 Kcal

$$\frac{\text{Grey Body}}{\text{Black Body}} = \frac{447.53}{614.28} = 0.72854$$

The calculated value of grey body radiation was assumed to be valid over the life of the animals. Although changing dimensions would favor more radiation when the animals were small, they were exposed to warmer bedding during the first part of the study. Therefore, the two effects were assumed to be compensating.

APPENDIX F

SCHEMATIC DIAGRAMS AND CSMP LISTINGS FOR THERMAL SECTION

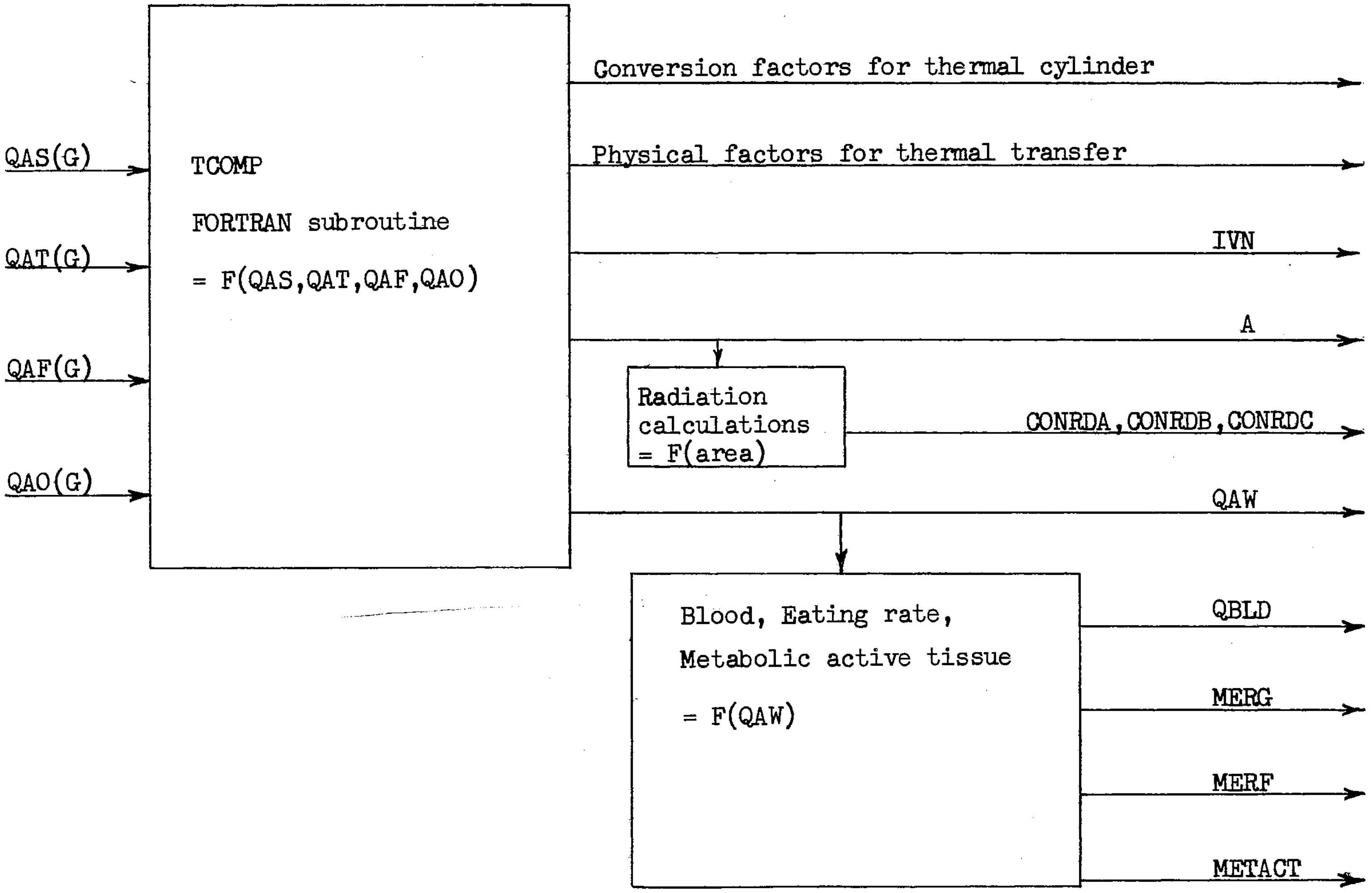


Figure 50. Major block diagram of composition computations.

```
********                         TCOMP SUBROUTINE                         ********
      SUBROUTINE  TCOMP(AA,VEN,  PC,DN,MIS,CA,KA,  TC,A,IVN    )
      REAL L, MIS, IVN,KA
      DIMENSION AA(1),VEN(1),PC(1),DN(1),MIS(1),CA(1),KA(1),P(1),TC(1)
      DIMENSION R(6),D(6),L(5)
      PI=MIS(7)
      W=PC(6)
      IF(W.LT.376.) A= AA(1)+W*(AA(2)+W*(AA(3)+W*(AA(4)+W*AA(5))))
      IF(W.GT.375.)A=0.16*W**0.59
C     CALCULATION OF AIR SPACE IN BODY
      VENT=VEN(1)+W*(VEN(2)+W*(VEN(3)+W*(VEN(4)+W*(VEN(5)+W*(VEN(6)+
     /W*VEN(7))))))
      IF(W.GT.375.00) VENT=VEN(8)*W**VEN(9)
      IVN=VENT
      VENT =VENT/20.
C     CALC.      OF ORGAN VOLUME
      DN(1)=PC(1)/(PC(1)+MIS(1)*VENT)
      DO 12 I=1,4
   12 PC(I)=PC(I)/W
      DN(7)=DN(1)*PC(1)+DN(2)*PC(2)+DN(3)*PC(3)+DN(4)*PC(4)
      R(5)=W*1000.*2./(A*10000.*DN(7))
      R(5)=R(5)/100.
      R(6)=R(5)+MIS(2)
      R(4)=R(5)-MIS(3)
      CA(7)=PI*R(4)*R(4)
      R(3)=((CA(7)-PC(4)*CA(7)/DN(4))/PI)**0.5
      R(2)=((PI*R(3)*R(3)-PC(3)*CA(7)/DN(3))/PI)**.5
      R(1)=((PI*R(2)*R(2)-PC(2)*CA(7)/DN(2)-PI*(R(5)*R(5)-R(4)*R(4)))
     //PI)**.5
      CA(1)=PI*R(1)*R(1)
      D(1)=R(1)/2.
      DO 10 I=1,6
      J=I+1
      IF(J.GT.6) GO TO 11
C     CAL. OF AVERAGE DISTANCE TO CENTER OF ELEMENTS
      D(J)=(R(I)+R(J))/2.
C     CAL. OF AREA-DISTANCE RELATIONSHIP ACROSS ELEMENT SURFACE
      L(I)=ALOG(D(J)/D(I))
C     CALC. OF AREAS OF EACH ELEMENT
      CA(J)=PI*(R(J)*R(J)-R(I)*R(I))
C     CAL. OF AREA-DISTANCE CONSTANTS
      KA(I)=2.*PI/L(I)
C             THERMAL CAPACITY OF EACH ELEMENT
   11 TC(I)=CA(I)*DN(I)*10000.0
   10 CONTINUE
      MIS(6)=DN(7)/(W*0.001)
      CA(6)= (CA(7)+CA(5))/(MIS(8)*CA(1)+MIS(4)*CA(2)+MIS(9)*CA(3)+
     1MIS(5)*CA(4)+MIS(9)*CA(5))
      CA(7) =MIS(8)*CA(1)+MIS(4)*CA(2)+MIS(9)*CA(3)
      CA(8)= 2.*R(5)/(R(1)*R(1))
      CA(9)  =2.0*PI*R(5)
      CA(10)=2.0*PI*R(6)
      CA(1)=CA(1)*MIS(8)
      CA(2)=CA(2)*MIS(4)
      CA(3)=CA(3)*MIS(9)
      CA(4)=CA(4)*MIS(5)
      CA(5)=CA(5)*MIS(8)
      RETURN
      END
```

```
******                COMPUTATIONS BASED ON AGE AND WEIGHT             ********
      INCON SAGE =284.

      CONSTANT TIMEQ=0.0,TINVLQ=24.0
      CONSTANT IWRATE=01.68, VWCON=0.58
      CONSTANT CNBMQ=1.738
      CONSTANT CBLDPC=0.077
      CONSTANT CTDNA=0.503,CTDNB=0.0,  CTDNC=0.0
      CONSTANT CFEDA=1.36
      CONSTANT         CFEDB=0.0,CFEDC=0.0
      CONSTANT ERA=-1.45,  ERB=0.0100386,  ERC=0.0
      CONSTANT CNERF=0.8
      CONSTANT CNTDNG=0.725
******   CONSTANTS FCR COMPUTING EQUIVALENT THERMAL CYLINDER           ********
      CONSTANT CNDIGG=0.0140,CNDIGF=.00832

      STORAGE AA(5),VEN(9)
      STORAGE PC(6),DN(7),MIS(9)
      STORAGE              CA(10),KA(5),     TC(6)
      TABLE AA(1)=.361996685,AA(2)=.0264628958,AA(3)=-.00016323189,...
      AA(4)=.5070253E-06,AA(5)=-.4916727E-09,VEN(1)=18.562, ...
      VEN(2)=-.94888,VEN(3)=0.019985,VEN(4)=-.00016172, ...
      VEN(5)=.640498E-06,VEN(6)=-.12344E-08,VEN(7)=.92738E-12,...
      VEN(8-9)=2*0.0,PC(1-6)=6*0.0,         DN(1)=1.0,DN(2)=1.45,...
      DN(3)=1.0,DN(4)=0.9,DN(5)=1.0,DN(6)=0.25,DN(7)=1.0,MIS(1)=3.,...
      MIS(2)= 0.005,MIS(3)=0.0025,MIS(4)=0.1,MIS(5)=0.2,MIS(6)=0.00,...
      MIS(7)=3.1415926536,MIS(8)=1.000,MIS(9)=1.000,  ...
                          CA(1-10)=10*0.0,KA(1-5)=5*0.0,...
      TC(1-6)=6*0.0


DYNAMIC

      AAGE=SAGE+TIME/24
      CNTDNF=CTDNA+AAGE*(CTDNB+AAGE*CTDNC)
      CNEXFA=(CNDIGF-CNDIGF*CNTDNF)/CNTDNF
      CNEXGA=(CNDIGG-CNDIGG*CNTDNG)/CNTDNG
      QAW=QAS+QAT+QAF+QAO
      IF (TIME.LT.TIMEQ) GO TO 75
      TIMEQ=TIMEQ+TINVLQ
```

```
******          COMPUTATIONS BASED ON AGE AND WEIGHT CONTINUED        ********
******   COMPUTATION OF EQUIVALENT THERMAL CYLINDER                   ********

      QAW=QAS+QAT+QAF+QAO
      PC(1)=QAO
      PC(2)=QAS
      PC(3)=QAT
      PC(4)=QAF
      PC(6)=QAW
      A,IVN     = TCOMP(AA,VEN,  PC,DN,MIS,CA,KA,  TC)
      TCG=TC(1)
      TCB=TC(2)
      TCM=TC(3)
      TCF=TC(4)
      TCS=TC(5)
      TCH=TC(6)
******   CALCULATION OF BMR AND BLOOD BASED ON WEIGHT OF ANINAL       ********

      METACT = MIS(8)*QAO+MIS(4)*QAS+MIS(9)*QAT+MIS(5)*QAF
      PBMR=CNBMQ*METACT
      QBLD=QAW*CBLDPC
      MERG=ERA + QAW*(ERB+QAW*ERC)
      MERF=CNERF*MERG
      QGPFED=CFEDA+QAW*(CFEDB+QAW*CFEDC)
******   CONVERSION FACTORS FOR POWER FLOW IN EQUIVALENT THERMAL CYLIN. ********

      PRVCX=VWCON*IVN*IWRATE
      PRVCON=CA(8)*PRVCX/A
      PSVCON=CA(9)*VWCON
      VWCONA=VWCON*A
      PFTCON=MIS(6)*CA(6)
      CNPHIG=HPG*CA(8)/A
      CNPHIF=HPF*CA(8)/A
      MRAD=CA(10)/A
   75 CONTINUE
```

```
******                    ENVIRONMENTAL MODELING                        ********
      FIXED LTEMP

******   CONSTANTS TO ESTABLISH ENVIRONMENT FOR HEAT TRANSFER           ********

      CONSTANT LTEMP=1
      CONSTANT RHUM=0.62
      CONSTANT TEORD=10.0 ,  TEAMP=0.0,  TEPS=0.0
      CONSTANT TXORD=10.0,  TXAMP=0.0,  TXPS=0.0
      CONSTANT TERORD=1.0,  TERAMP=0.0,  TERPS =0.0
      CONSTANT TSNORD=0000.0,TSNAMP=0.0,  TSNPS=0.0
      CONSTANT FREQ=0.2618
      CONSTANT ESW=0.75,ELW=0.95, SBC=4.93E-08
      CONSTANT CPA=1.00, CPB=0.70,CPC=1.00
      CONSTANT FEA=0.0,       EA=1.0,      AREAA=100.0
      CONSTANT FEB=1.0,     EB=1.0,        AREAB=100.0
      CONSTANT FEC=0.0 ,    EC=1.0,           AREAC=100.0
INITIAL
******   COMPUTATION OF RADIATION RESISTANCES OF THE ENVIRONMENT        ********

      IF(LTEMP-3)801,802,803
  803 EEA=(1.-EA)/(EA*AREAA)
  802 EEC=(1.-EC)/(EC*AREAC)
  801 EEB=(1.-EB)/(EB*AREAB)
******   COMPUTATION OF ENVIRONMENT HUMIDITY RATIO--ASSUMED CONSTANT     ********

      TE=TEORD
      TEF=(491.69+9.*TE/5.)
      TELGG=ALOG(TEF)
      TEFX= (54.6329-12301.688/TEF-5.16923*TELGG)
      PVE=RHUM*EXP(TEFX)
     WE=0.6219*(PVE/(14.696-PVE))

DYNAMIC
******   COMPUTATION OF RADIATION FACTORS BASED UPON AREA OF ANIMAL     ********

      IF(LTEMP-3)811,812,813
  813 AZ=CPA*A
      IF(FEA.LT.0.000001) GO TO 21
      IF( AZ.LT.0.000001) GO TO 21
      EAA=(1.-ESW)/(ESW*AZ)
      FAA=1./(AZ*FEA)
      RRADA=EAA+FAA+EEA
      CONRDA=SBC/RRADA
      GO TO 24
   21 CONRDA=0.0
   24 CONTINUE
```

```
******                   ENVIRONMENTAL MODELING CONTINUED                   *********
  812 AC=CPC*A
      IF(FEC.LT.0.000001) GO TO 23
      IF( AC.LT.0.000001) GO TO 23
      EAC=(1.-ELW)/(ELW*AC)
      FAC=1./(AC*FEC)
      RRADC=EAC+FAC+EEC
      CONRDC=SBC/RRADC
      GO TO 26
   23 CONRDC=0.0
   26 CONTINUE

  811 AB=CPB*A
      IF(FEB.LT.0.000001) GO TO 22
      IF( AB.LT.0.000001) GO TO 22
      EAB=(1.-ELW)/(ELW*AB)
      FAB=1./(AB*FEB)
      RRADB=EAB+FAB+EEB
      CONRDB=SBC/RRADB
      GO TO 25
   22 CONRDB=0.0
   25 CONTINUE

*@****   CALCULATION OF RADIATION TRANSFER                                  ********

      THFOR=(TH+273.16)**4
      TESIN  =SINE(0.,FREQ  ,TEPS )
      TE=TEAMP*TESIN +TEORD
PROCEDURE PRAD=TEMPXX(TE,THFOR)
      GO TO (821,822,823,824),LTEMP
  824 TSNSIN =SINE(0.,FREQ  ,TSNPS)
      TSUN=TSNAMP*TSNSIN+TSNORD
      TEA=TSUN +273.16
      TEAFOR=TEA**4
      PRA=CONRDA*(THFOR-TEAFOR)
  823 TERSIN =SINE(0.,FREQ  ,TERPS)
      TEARTH = TERAMP*TERSIN+TERORD
      TEC=TEARTH  + 273.16
      TECFOR=TEC**4
      PRC=CONRDC*(THFOR-TECFOR)
  822 TXSIN=SINE(0.0,FREQ , TXPS)
      TX=TXAMP*TXSIN+ TXORD
      GO TO 825
  821 TX=TE
      TEB=TX+273.16
  825 TEBFOR=TEB**4
      PRB=CONRDB*(THFOR-TEBFOR)
      PRDOUT=(PRA+PRB+PRC)
      PRAD=PRDOUT*MRAD
ENDPRO
```

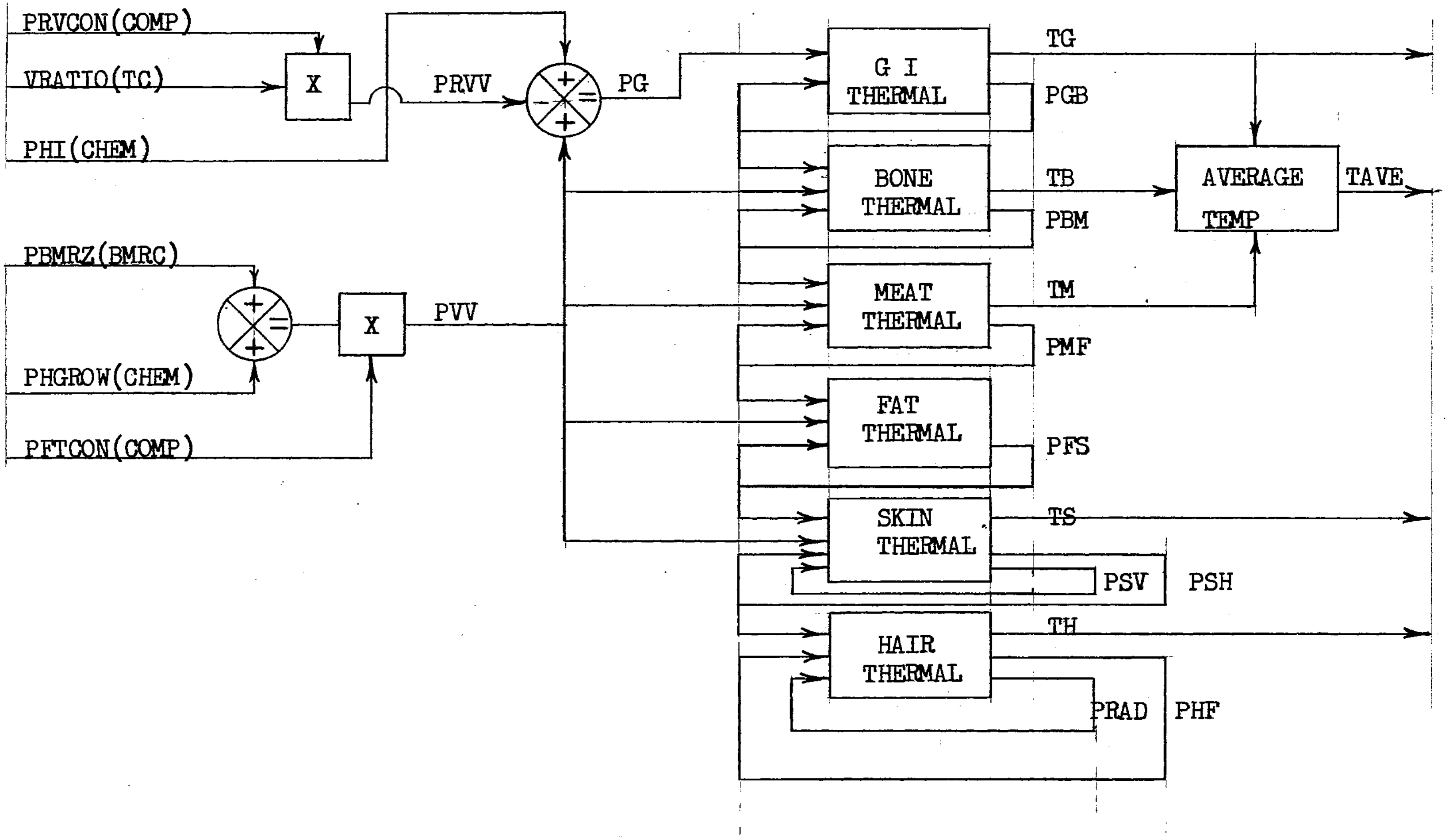


Figure 51. Major flowchart of thermal section showing forcing functions and module interconnections.

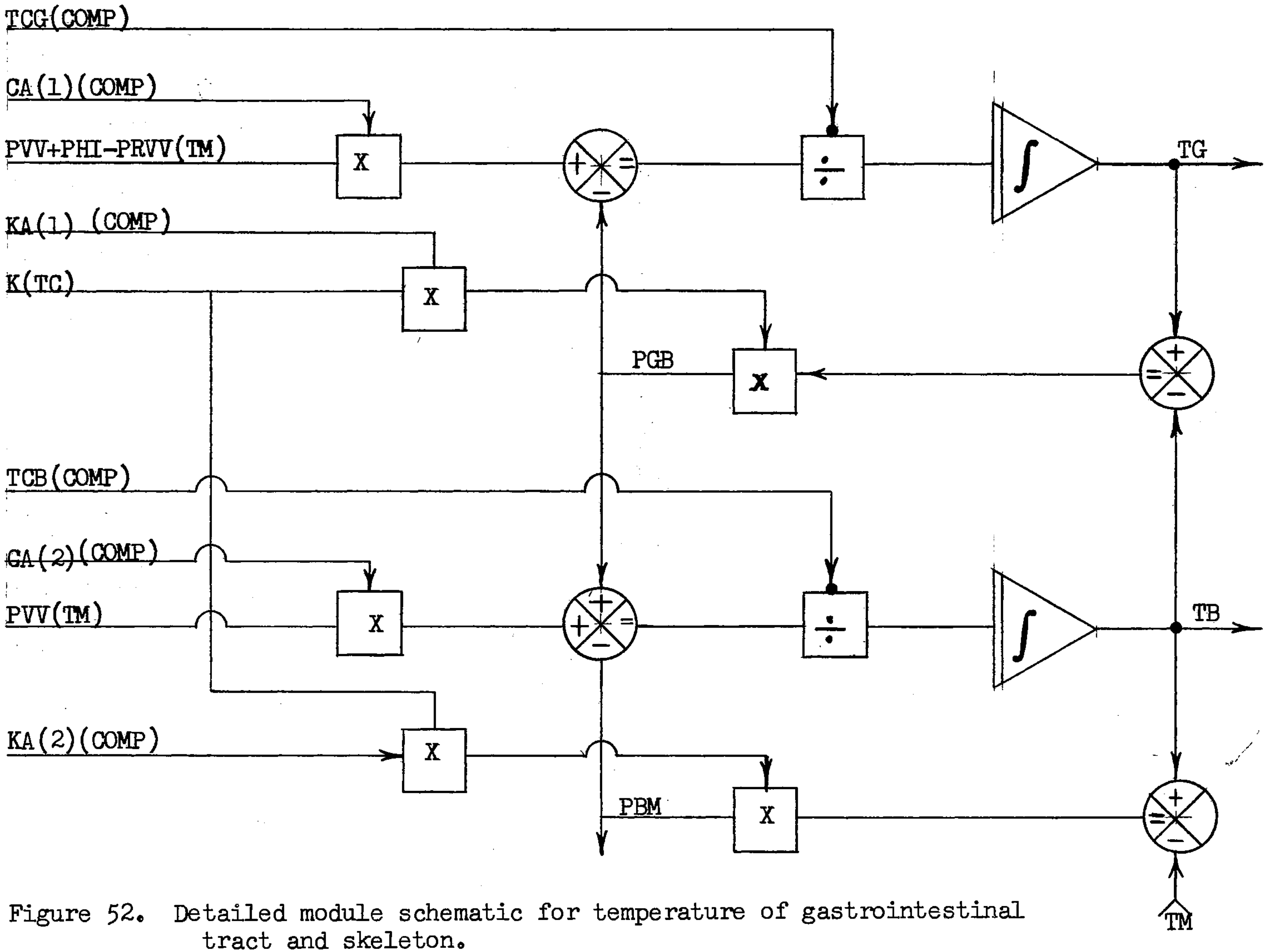


Figure 52. Detailed module schematic for temperature of gastrointestinal tract and skeleton.

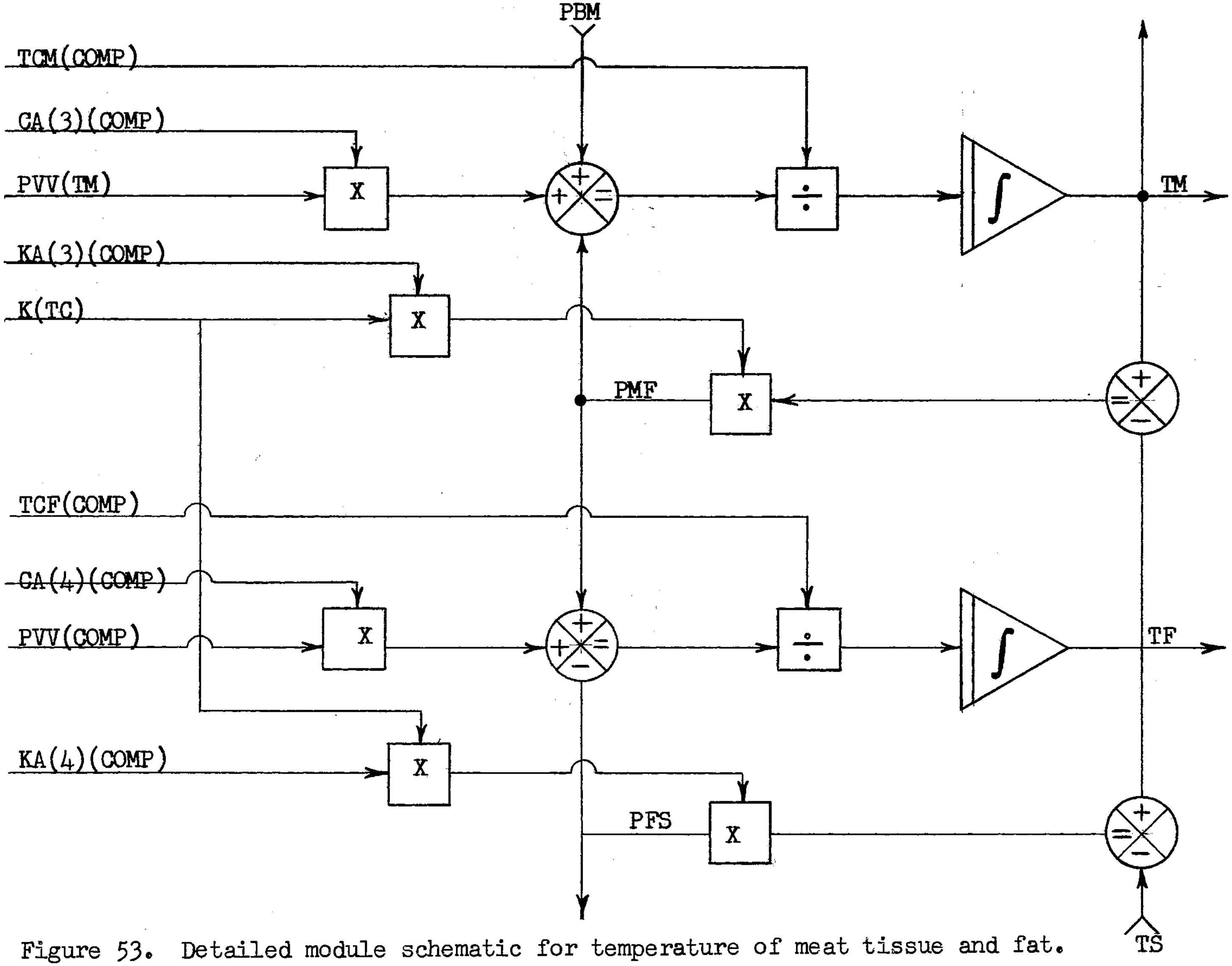


Figure 53. Detailed module schematic for temperature of meat tissue and fat.

```
******   THERMAL SECTION, GASTROINTESTINAL TRACT,SKELETON,MEAT, & FAT    *********
      INCON TGO=39.230,TBO=35.61,TMO=34.70,TFO=33.12
DYNAMIC
******   TEMPERATURE OF GASTROINTESTINAL TRACT                           *********
      PGB=KA(1)*K*(TG-TB)
      PRVV=PRVCON*VRATIO
      PRVOUT=PRVCX*VRATIO
      PVVX=PBMRZ*PFTCON
      PVV=PHGROW*PFTCON+PVVX
      PGX=PRVV*CA(1)
      PG=(PVV+PHI)*CA(1)-PGX
      DTGX=PGB/TCG
      DTG=PG/TCG-DTGX
      TG=INTGRL(TGO,DTG)
******   TEMPERATURE OF SKELETON                                         *********
      PBM=KA(2)*K*(TB-TM)
      PB=PVV*CA(2)
      DTBX=(PGB-PBM)/TCB
      DTB=PB/TCB+DTBX
      TB=INTGRL(TBO,DTB)
******   TEMPERATURE OF MEAT TISSUE                                      *********
      PMF=KA(3)*K*(TM-TF)
      PM=PVV*CA(3)
      DTMX=(PBM-PMF)/TCM
      DTM=PM/TCM+DTMX
      TM=INTGRL(TMO,DTM)
******   TEMPERATURE OF FAT                                              *********
      PFS=KA(4)*K*(TF-TS)
      PF=PVV*CA(4)
      DTFX=(PMF-PFS)/TCF
      DTF=PF/TCF +DTFX
      TF=INTGRL(TFO,DTF)
```

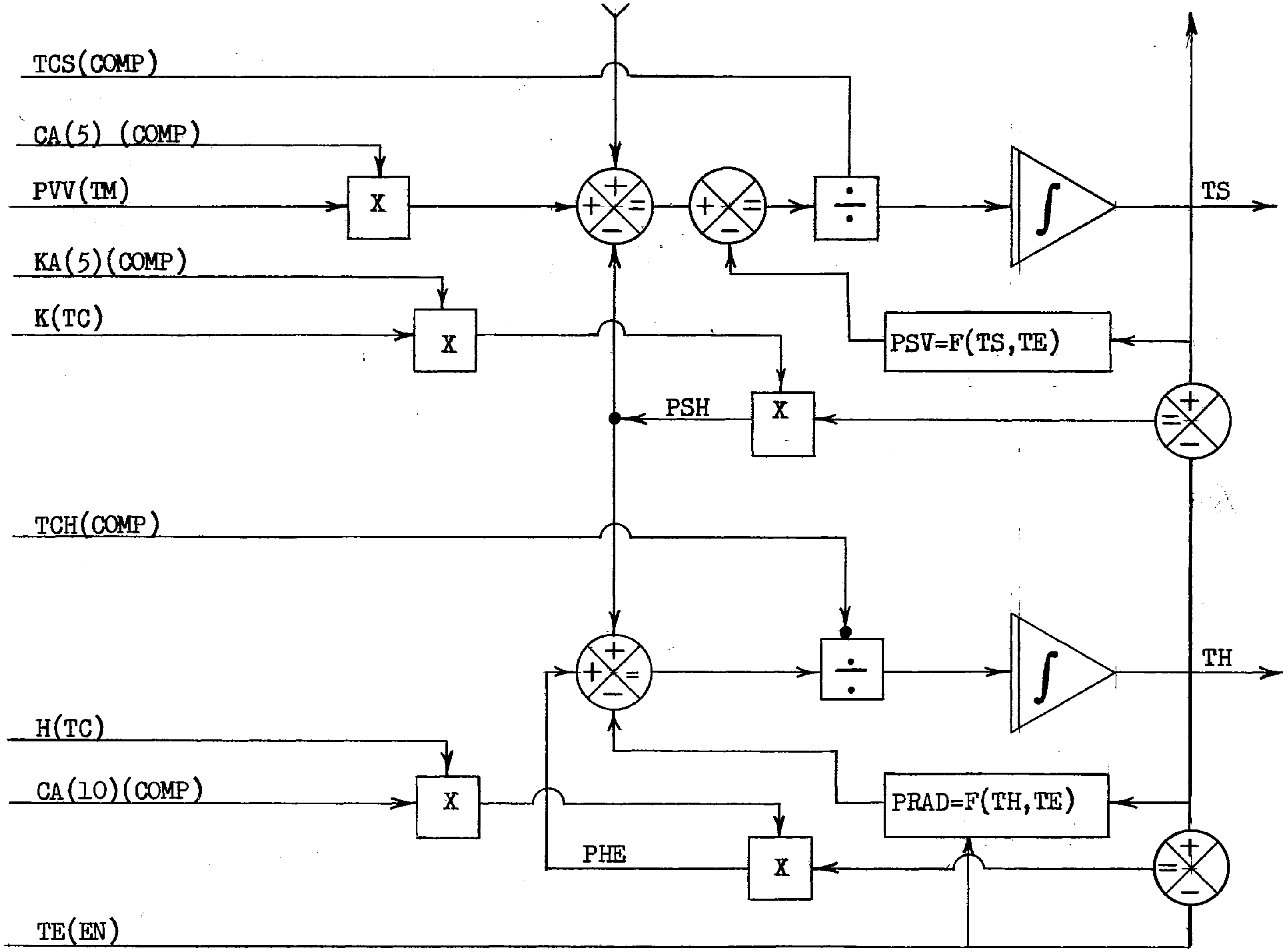


Figure 54. Detailed module schematic for temperatures of skin and hair.

```
******              THERMAL SECTION, SKIN AND HAIR                                    ********
       INCON    TSO=32.47,THO=22.97
       CONSTANT TSLESS=10000., TSPLUS=100000.0
       CONSTANT CTOFF=0.5
       CONSTANT              PRFAT=0.0, PRA=0.0,PRC=0.0

DYNAMIC

******    ??? IS RECOMPUTATION OF WS REQUIRED   ???                                  ********
       IF (TS.LT.TSLESS) GO TO 18
       IF (TS.GT.TSPLUS) GO TO  18
       GO TO 19

******    RECOMPUTE WS                                                               ********
   18  TSLESS=TS-CTOFF
       TSPLUS=TS+CTOFF
       TSF=(491.69+9.*TS/5.)
       TSLGG=ALOG(TSF)
       TSFX= (54.6329-12301.688/TSF-5.16923*TSLGG)
       PSS=EXP(TSFX)
      WS=0.6219*(PSS/(14.696-PSS))
   19  CONTINUE
  SORT

******    COMPUTE MOISTURE LOSS                                                      ********
       M=(WS-WE)*HB*HM/(HB+HM)
       PSV=PSVCON*M
       PSVOUT=VWCONA*M

******    TEMPERATURE OF SKIN                                                        ********
       PSHX=KA(5)*KH*TS
       PSHY=KA(5)*KH
       PSH=PSHX-PSHY*TH
       PS=PVV*CA(5)
       DTSX=PS/TCS
       DTSY=(PFS-PSV)/TCS
       DTS=DTSX+DTSY-PSH/TCS
       TS=INTGRL(TSO,DTS)

******    TEMPERATURE OF HAIR                                                        ********
       PHEX=CA(10)*H
       PHEY=CA(10)*H*TE
       PHE=PHEX*TH-PHEY
       PHEOX=A*H
       PHEOY=A*H*TE
       PHEOUT=PHECX*TH-PHEOY
       DTHX=PRAD/TCH
       DTH=(PSH-PHE)/TCH-DTHX
       TH=INTGRL(THO,DTH)
       POWERX=PRVOUT+PSVOUT+PRDOUT
       POWER=POWERX+PHEOUT
       POWERA=POWER/A
```

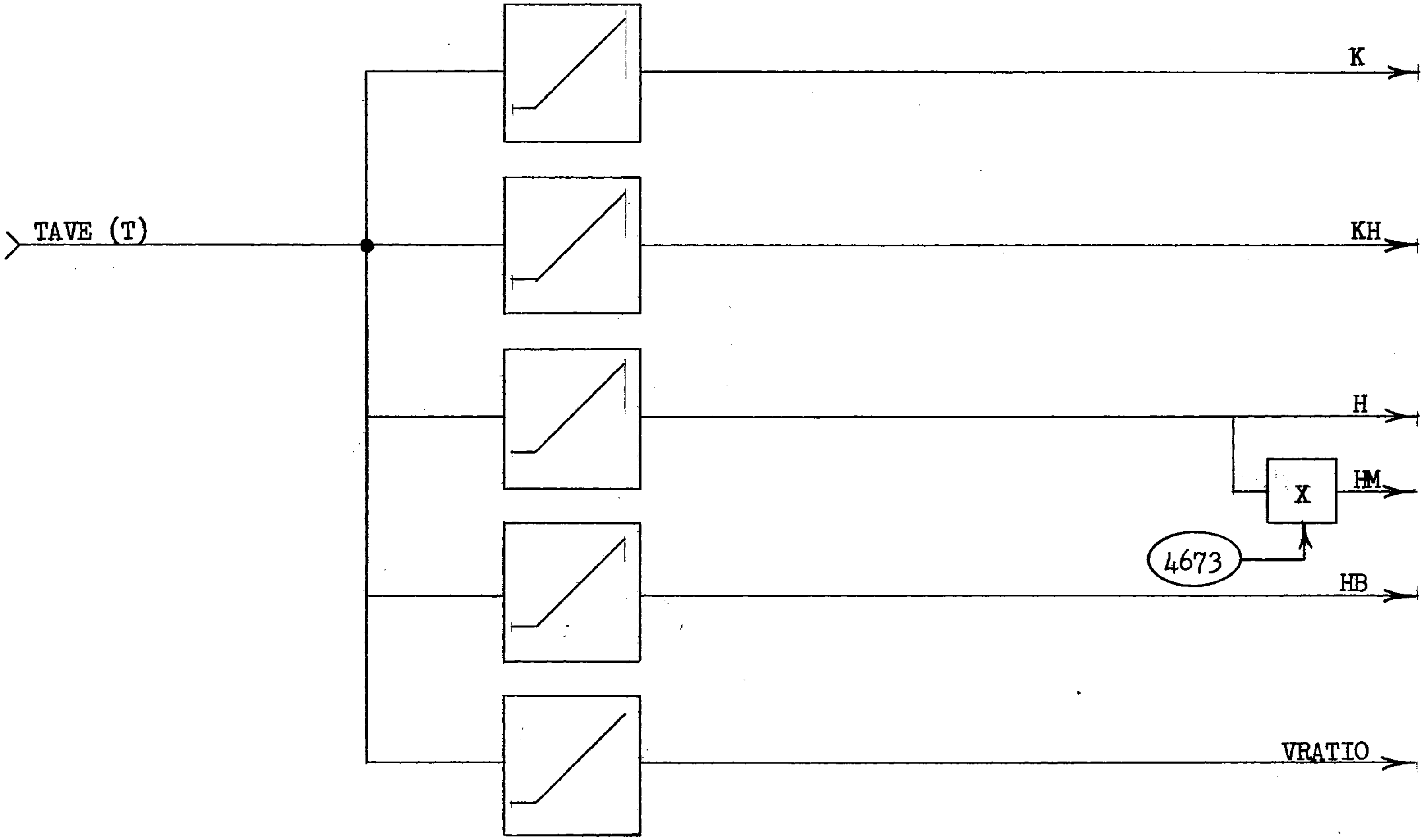


Figure 55. Thermal control module schematic showing heat transfer coefficients as a function of the average body temperature.

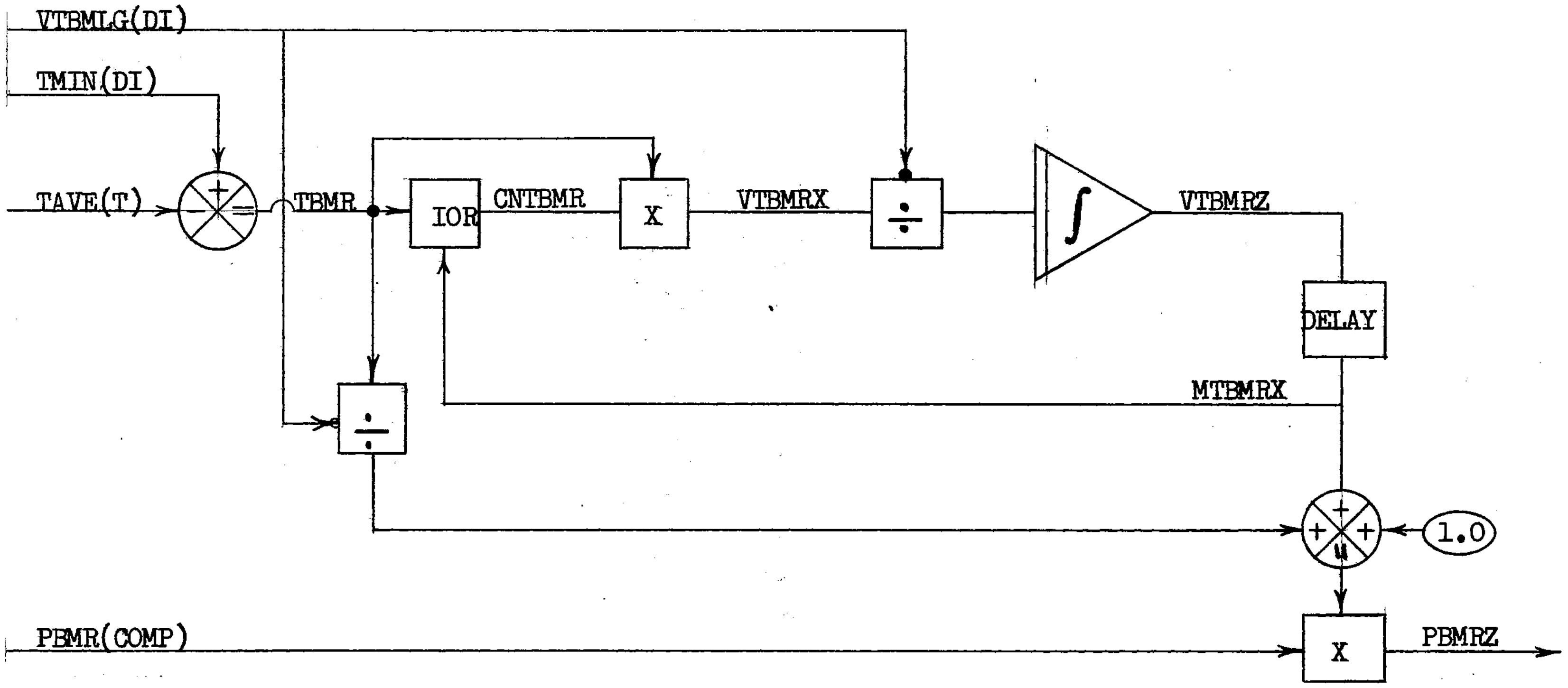


Figure 56. Detailed module schematic of the basal metabolic rate controller.

```
******                 TEMPERATURE CONTROL MODULES                      ********
      INCON PBMRO=0.00
******   CONSTANTS FOR THERMAL CCNTROL = F(TAVE)                        ********

      CONSTANT HO=-307.142568,  HA =8.363887
      CONSTANT KO=-122.48674,KAA=3.34900
      CONSTANT KHO=-3.593319, KHA=0.097591
      CONSTANT CVRA=-158.439207,  CVRB=4.296061
      CONSTANT HBA=-33815.0154, HBB=942.7041
      CONSTANT CMOIST= 4673.0
      CONSTANT TCNMN=37.10
      CONSTANT TMAX=40.00
      CONSTANT P=0.01
      CONSTANT TMIN=37.22,VTBMLG=24.0
      CONSTANT CITX=0.000001

DYNAMIC

******   CONTROL FUNCTIONS BASED UPON TAVE                              ********

   30 TAVE=(TG*CA(1)+TB*CA(2)+TM*CA(3))/CA(7)
      IF (TAVE.LT.TCNMN) GO TO 20
      K=KO+KAA*TAVE
      KH=KHO+KHA*TAVE
      H=HO+HA*TAVE
      HB=HBA+HBB*TAVE
      HM=CMOIST*H
      VRATIO=CVRA+CVRB*TAVE
   20 CONTINUE

******    ADJUSTMENT OF BMR BASED UPON TAVE ERROR SIGNAL                ********

      TBMR=TMIN-TAVE
PROCEDURE  CNTBMR=TBMRZZ(TBMR,MTBMZ)
      CNTBMR=0.0
      IF(TBMR.GT.0.0 )  CNTBMR=1.0
      IF(MTBMZ.GT.0.0) CNTBMR=1.0
ENDPRO
      VTBMRX=TBMR*CNTBMR/VTBMLG
      VTBMRZ=INTGRL(PBMRO,VTBMRX)
      MTBMRX=CNTBMR*VTBMRZ-CITX
      MTBMZ=DELAY(1,P,MTBMRX)
      PBMRZ=PBMR*(MTBMZ+1.0 +TBMR/VTBMLG)
```

APPENDIX G

SCHEMATIC DIAGRAMS AND CSMP LISTINGS FOR DIGESTIVE SECTION

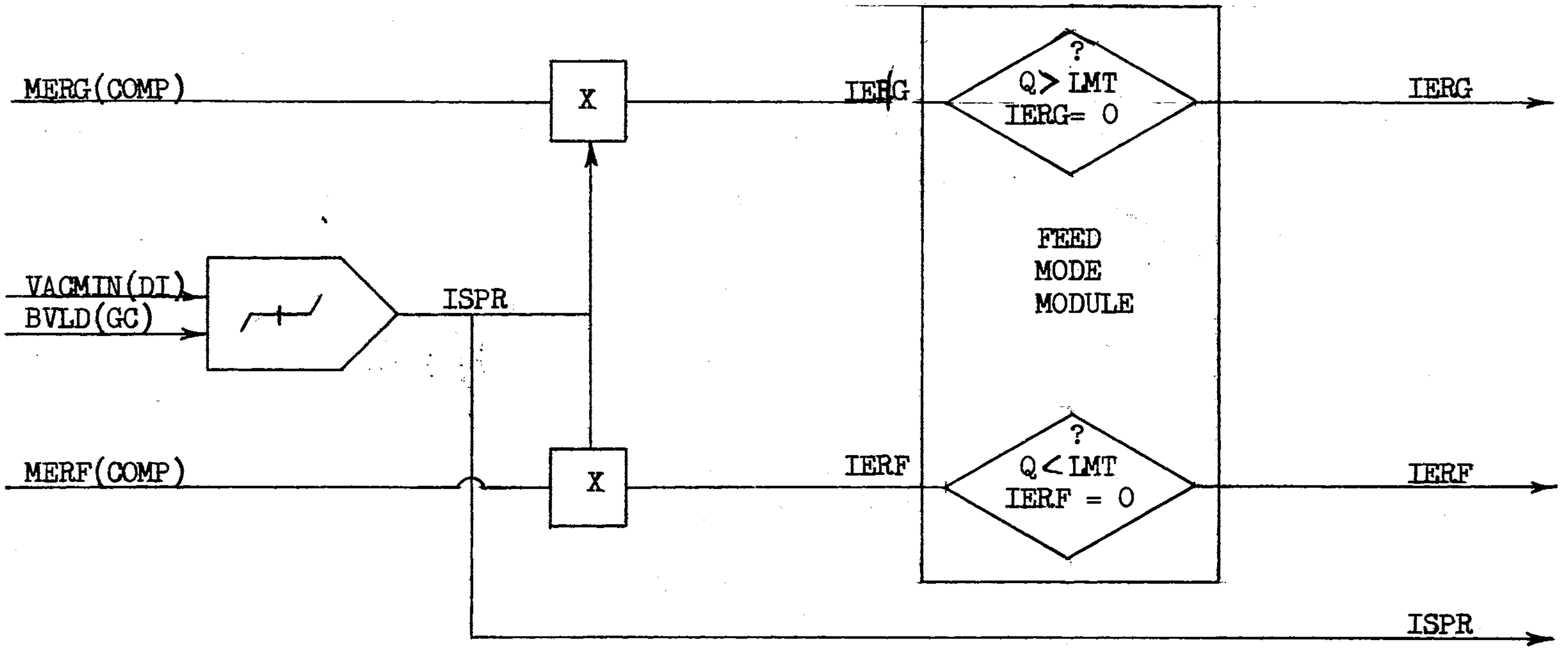


Figure 57. Schematic of the eating control module.

```
******                          EATING CONTROL                           ********
      INCON QEATGO=0.0,QEATFO=0.0
      INCON QEATGL=0.0
      INCON FEDKNT =0.0

      CONSTANT ACTREF=5.0
      CONSTANT TFEED=0.0,TINVL=12.0
      CONSTANT OFFSET=0.5
      CONSTANT IX=0.0, CITX=0.00001

INITIAL

      RATREF=ACTREF+OFFSET

DYNAMIC
 NOSORT

      IF(QEATG.GT.QEATGL) GO TO 80
      IERG= MERG*ISPR
      IERF=0.0
      GO TO 90
   80 IERF= MERF*ISPR
      IERG=0.
   90 CONTINUE

******   AMOUNT OF GRAIN AND FORAGE CONSUMED                             ********

      QEATF=INTGRL(QEATFO,IERF)
      QEATG=INTGRL(QEATGO,IERG)

******   REST OF MODEL INSERTED HERE                                     ********
******   ???  EATING STATUS    ?????                                     ********

      IF(KEEP.LT.1) GO TO 85
      ISPR=0.0
      IF(VBLD.LT.ACTREF)ISPR=1.0
      KRAT=0.0
      IF(VBLD.LT.RATREF) KRAT=1.0
      IF (TAVE.GT.TMAX) ISPR=0.0
      IS=ISPR
      IF(IS.LT.CITX) GO TO 911
      IF(IS.LT.IX) GO TO 911
      FEDKNT=FEDKNT+1.0
  911 IX=ISPR+CITX

******   ??? TIME TO FEED MORE GRAIN  ???                                ********
      IF(TIME.LT.TFEED) GO TO 85
      QGRAIN=QEATGL-0.5*QGPFED
      IF (QEATG.LT.QGRAIN) GO TO  85
      QEATGL=QEATGL+QGPFED
      TFEED=TFEED+TINVL
   85 CONTINUE
 SORT
```

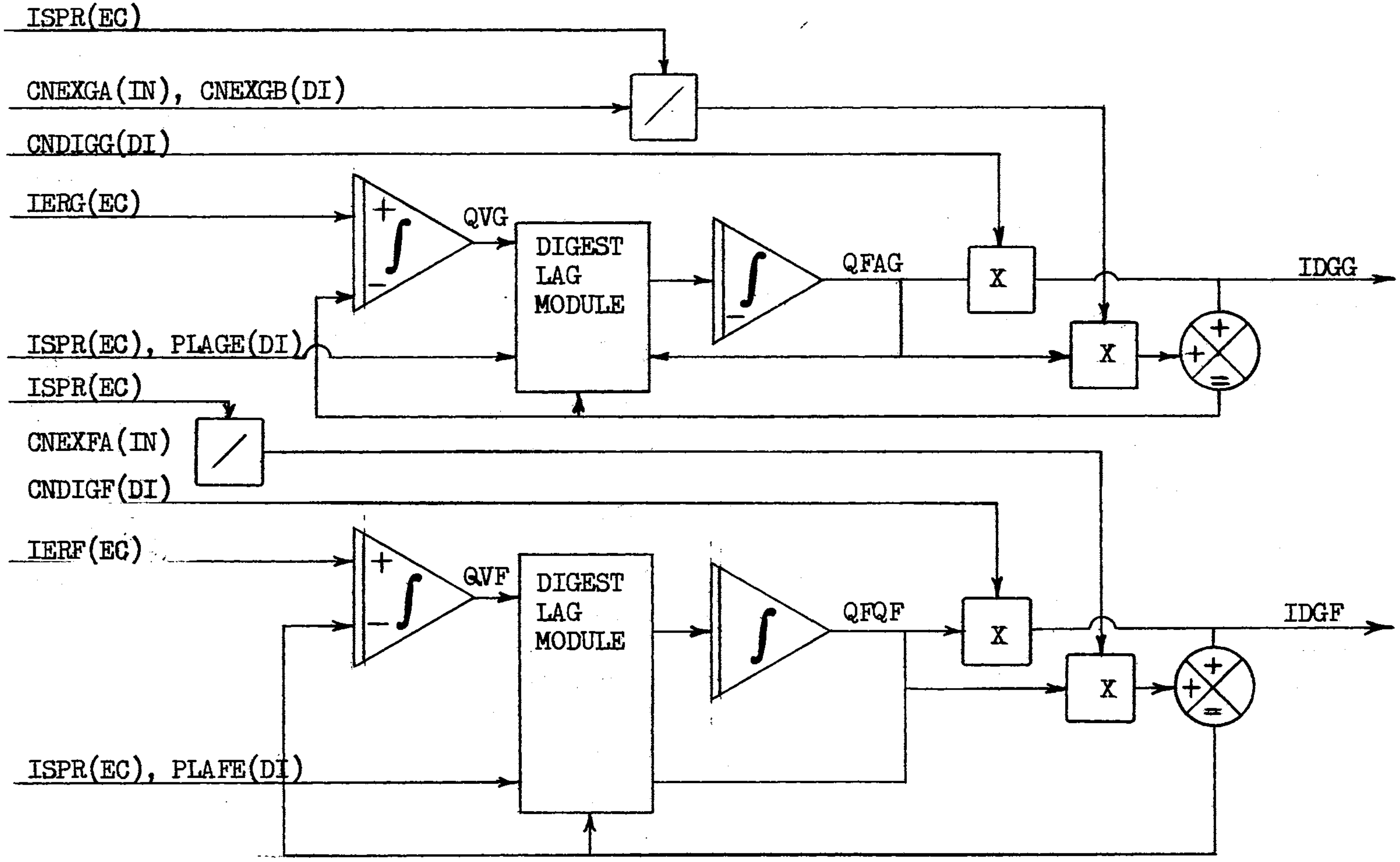


Figure 58. Schematic of the digestive module illustrating the digestive lag and the depression of digestibility.

```
******                    DIGESTIVE SECTION                           *********
      INCON QVGO=4.19,QVFO=6.35
      INCON  QFAFO=06.35,QFAGO= 4.19

      CONSTANT PLAGE=1.2,  PLAFE=1.2
      CONSTANT             CNEXGB=0.0
      CONSTANT              CNEXFB=0.0
      CONSTANT CNDIGG=0.0140,CNDIGF=.00832

DYNAMIC

******   ADJUST TIME CONSTANTS FOR AVAILABLE FATTY ACIDS FROM FOOD     *********

      IEXG=(CNEXGA+CNEXGB*ISPR)*QFAG
      IDGG=CNDIGG*QFAG
      IEXF=(CNEXFA+CNEXFB*ISPR)*QFAF
      IDGF=CNDIGF*QFAF
PROCEDURE  DQFAF,DQFAG=EATXXX(IERG,IDGF,IDGG,IEXG,IEXF,ISPR)
      IF (ISPR.GT.0.0) GO TO 851
      IF(QFAG.LT.QVG ) GO TO 853
      DQFAG=(-IDGG-IEXG)
      GO TO 854
  851 IF(IERG.LT.0.0001) GO TO 852
  853 DQFAG=(QVG-QFAG)/PLAGE
  854 IF(QFAF.LT.QVF ) GO TO 856
      DQFAF=(-IDGF-IEXF)
      GO TO 855
  856 DQFAF=(QVF-QFAF)/PLAFE
      GO TO 855
  852 DQFAF=(QVF-QFAF)/PLAFE
      IF(QFAG.LT.QVG ) GO TO 857
      DQFAG=(-IDGG-IEXG)
      GO TO 855
  857 DQFAG=(QVG-QFAG)/PLAGE
  855 CONTINUE
ENDPRO

******   DIGESTION OF FORAGE                                           *********

      QFAF=INTGRL(QFAFO,DQFAF)
      DQVF=IERF-IDGF-IEXF
      QVF=INTGRL(QVFO,DQVF)

******   DIGESTION OF GRAIN                                            *********

      QFAG=INTGRL(QFAGO,DQFAG)
      DQVG=IERG-IDGG-IEXG
      QVG=INTGRL(QVGO,DQVG)
```

APPENDIX H

SCHEMATIC DIAGRAMS AND CSMP LISTINGS FOR CHEMICAL SECTION

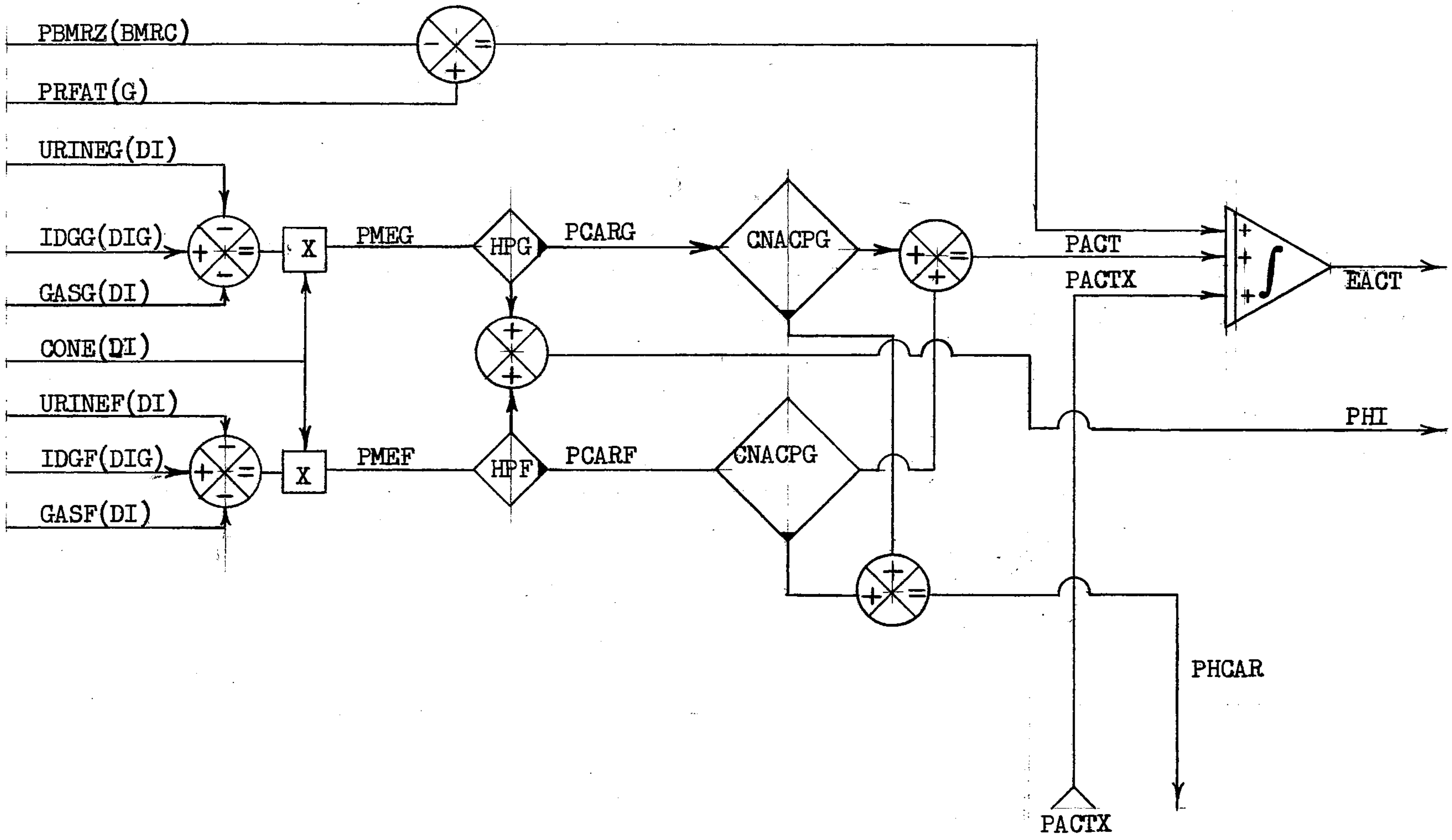


Figure 59. Detailed schematic of the acetic acid module of the chemical section, illustrating the conversion of digested nutrients to energy.

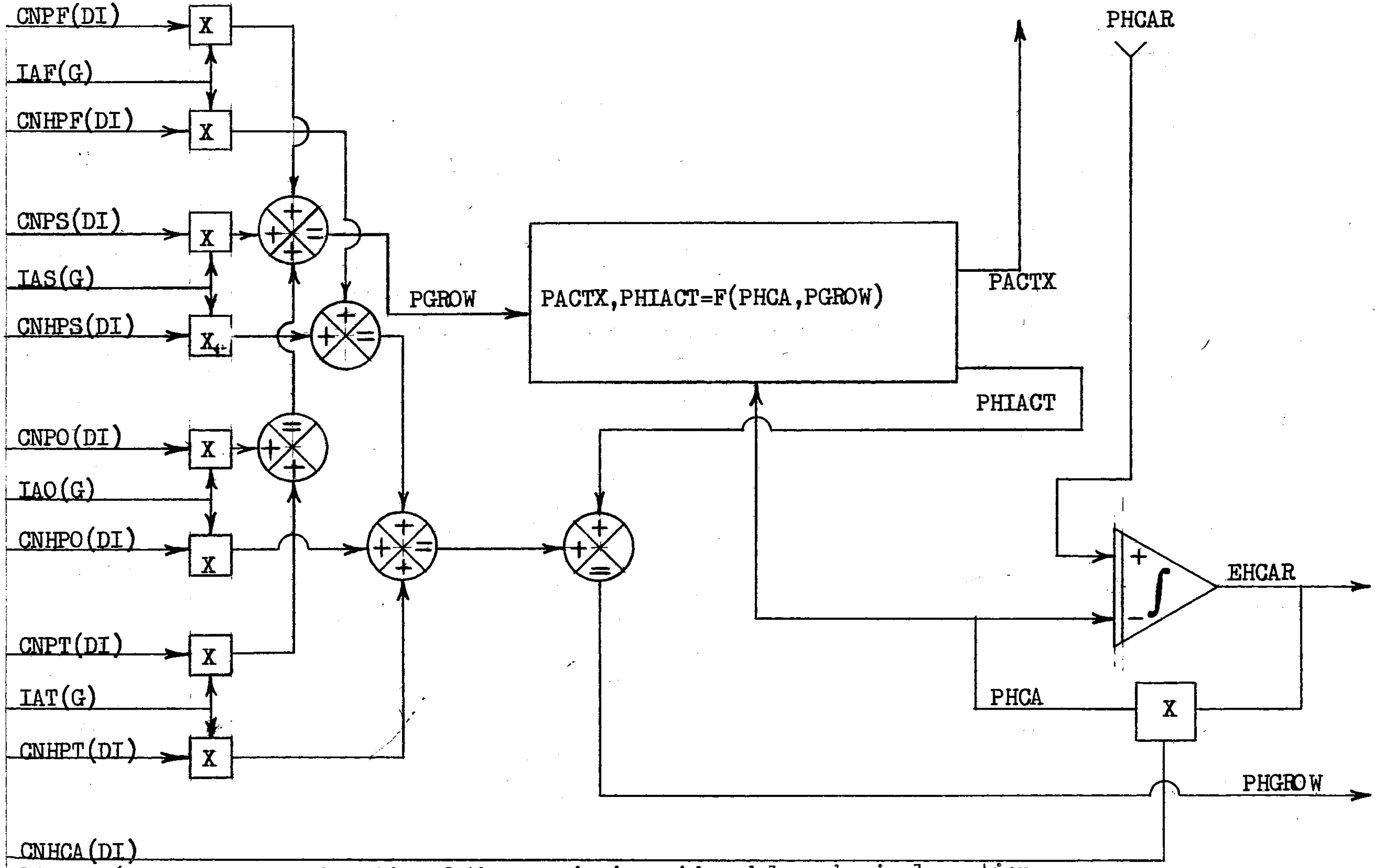


Figure 60. Detailed schematic of the propionic acid module, chemical section.

```
******                        CHEMICAL SECTION                        ********
      INCON EACTO=155.0
      INCON EHCO=113.0
      CONSTANT CNHCA=2.0
      CONSTANT CNHPOT=100.0, CNHPS=160.0,CNHPF=680.0
      CONSTANT           CNACPG=.279, CNACPF=.577
      CONSTANT CNPHCA=0.00, CNPHC=0.02,CNPACT=0.14
      CONSTANT HPG=0.06,HPF=0.12
      CONSTANT CNPOT=1220.00,CNPS=2000.00, CNPF=10080.0
      CONSTANT          CONE=4409.
      CONSTANT GASG=0.07,GASF=0.06
      CONSTANT URINEG=.120,URINEF=0.12
INITIAL

      CNMEG=(1.0-GASG-URINEG)*CONE
      CNMEF=(1.0-GASF-URINEF)*CONE
      MHCPF=1.0-CNACPF
      MHCPG=(1.0-CNACPG)
      MMEF=(1.0-HPF)
      MMEG=(1.0-HPG)

DYNAMIC
******   STATUS OF ENERGY IN THE FORM OF ACETATE                       ********


      PMEF=CNMEF*IDGF
      PCARF=MMEF*PMEF
      PMEG=CNMEG*IDGG
      PCARG=MMEG*PMEG
      PHI=PMEG*CNPHIG+PMEF*CNPHIF
      PACT=CNACPG*PCARG+CNACPF*PCARF
      DEACT=(PACTX+PACT-PBMRZ+PRFAT)
      EACT=INTGRL(EACTO,DEACT)

******   STATUS OF ENERGY IN FORM OF HIGHER CARBONS                    ********

      PHCAR=MHCPG*PCARG+MHCPF*PCARF
      PHCA=EHCAR*CNHCA
      DEHC=PHCAR-PHCA
      EHCAR=INTGRL(EHCO,DEHC)
      PGROW=(IAO+IAT)*CNPOT+IAS*CNPS+IAF*CNPF
      PHGROW=PHIACT+(IAO+IAT)*CNHPOT+IAS*CNHPS+IAF*CNHPF
      PACTG=PHCA-PGROW
PROCEDURE PACTX,PHIACT=ACTGRW(CNPHCA,CNPHC,CNPACT,PACTG,PGROW,PHCA)
      IF (PACTG.LT.0.0) GO TO 31
      PACTX=(1.0-CNPHCA)*PACTG-CNPHC*PGROW
      PHIACT=CNPHCA*PACTG+CNPHC*PGROW
      GO TO 32
   31 PACTX=(1.0+CNPACT)*PACTG-CNPHC*PHCA
      PHIACT=CNPHC*PHCA-CNPACT*PACTG
   32 CONTINUE
ENDPRO
```

APPENDIX I

FLOW CHART AND LISTING FOR FINAL MODEL AND OPTIMIZATION PACKAGES

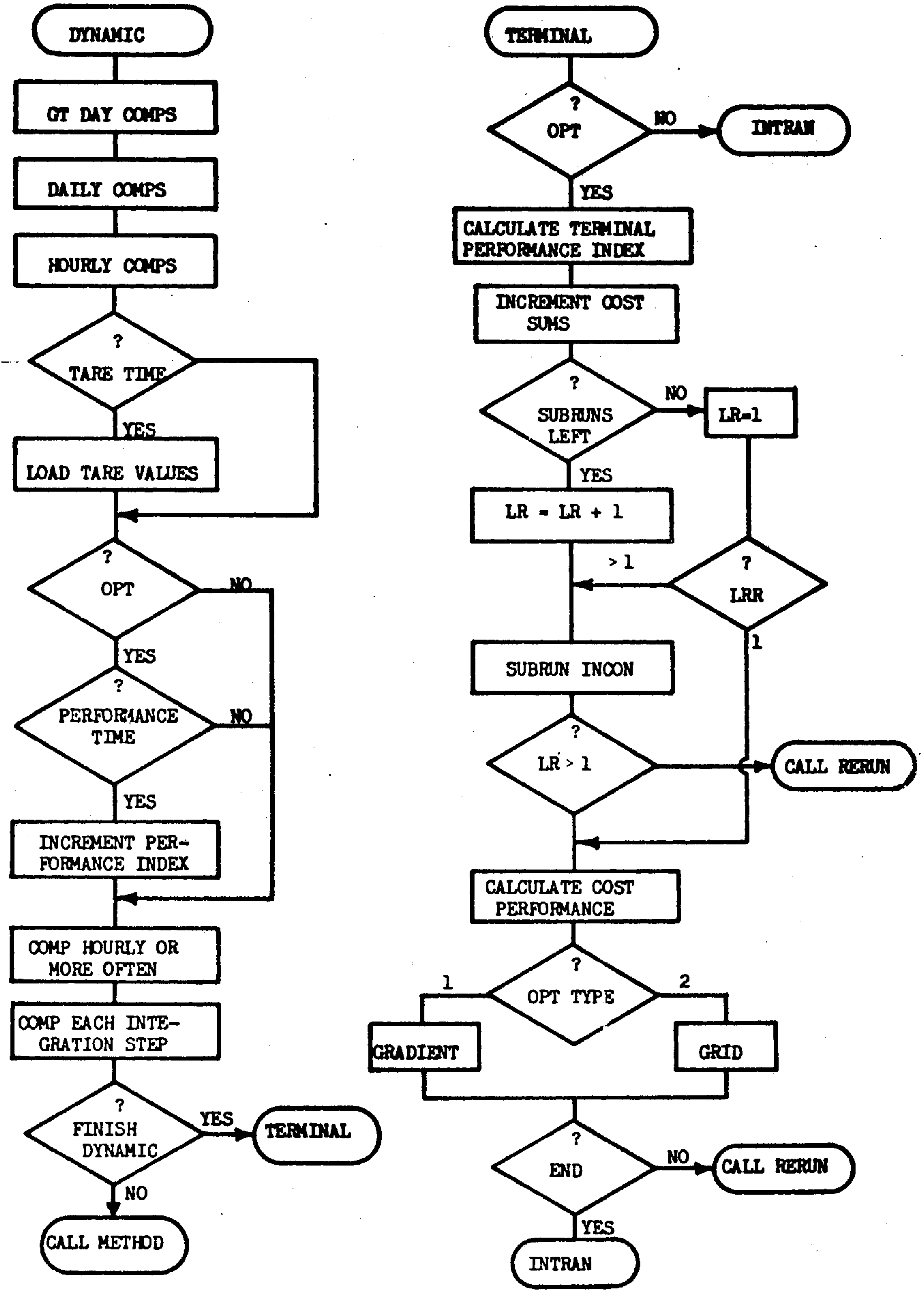


Figure 61. Flow chart for revised final model and generalized routines for performance index computation.

```
$LIST

********                          UPDATE SUBROUTINE                         ********

      SUBRCUTINE UPDATE
      COMMON  ZZ9901(5),IZ9901,ZZ9902,IZ9902,ZZ9903,IZ9903,ZZ9991(54)
      COMMCN  TIME  ,DELT  ,DELMIN,FINTIM,PRDEL ,OUTDEL
      COMMCN  CEATG ,QEATF ,TG    ,TS    ,TH    ,QAF   ,QAO   ,QAS
     1,QAT   ,QFAG  ,QFAF  ,EACT  ,EHCAR ,QVF   ,CVG   ,IAF   ,IAO
     1,IAS   ,IAT   ,TB    ,TF    ,TM    ,VTBMRZ,TAVBLD,VACERZ
      COMMON  IERGX ,IERF  ,DTG   ,DTS   ,DTH   ,IFF   ,ZZ0039,ZZ0037
     1,ZZ0038,DQFAG ,DQFAF ,DEACT ,DEHC  ,DQVF  ,DQVG  ,DIAF  ,DIAO
     1,DIAS  ,DIAT  ,DTB   ,DTF   ,DTM   ,VTBMRX,TAVBX ,VFATX
      COMMON  QEATGO,QEATFO,TGO   ,TSO   ,THC   ,SCAF  ,SCAO  ,SQAS
     1,SCAT  ,QFAGO ,QFAFO ,EACTO ,EHCO  ,QVFO  ,QVGO  ,SIAF  ,SIAO
     1,SIAS  ,SIAT  ,TBO   ,TFO   ,TMO   ,PBMRC ,TAVEO ,VACO
      COMMON  NPCRD ,NVEC  ,LTEMP ,LFAT  ,SAGE  ,CNBMQ ,TMIN  ,TINVL
     1,CFEDA ,CFEDB ,CFEDC ,PLAGE ,CNDIGG,DF    ,URINEG,GASG  ,HPG
     1,CNACPG,CNERF ,PLAFE ,CNDIGF,CTDNA ,CTDNB ,CTDNC ,URINEF,GASF
     1,HPF   ,CNACPF,RHUM  ,TEORD ,TEAMP ,TEPS  ,TXORD ,TXAMP ,TXPS
     1,CPB   ,FEB   ,EB    ,AREAB ,TERORD,TERAMP,TERPS ,CPC   ,FEC
     1,EC    ,AREAC ,TSNORD,TSNAMP,TSNPS ,CPA   ,FEA   ,EA    ,AREAA
     1,OPT   ,LRR   ,LPN   ,LNC   ,LND   ,LNT   ,TARTIM,CTDNGA,CTDNGB
     1,CTDNGC,RTBTIM,RTCTIM,CSTGA ,CSTGB ,CSTGC ,DA(2)
      COMMCN  ERA   ,ERB   ,ERC   ,ACTREF,CORVPR,CNVPR ,CNEXGB,CNEXFB
     1,CRN   ,CRFA  ,CRFD  ,CRFO  ,CROA  ,CROD  ,CROO  ,CRSA  ,CRSD
     1,CRSO  ,CRTA  ,CRTD  ,CRTO  ,CHFA  ,CHFD  ,CHFO  ,CHOA  ,CHOD
     1,CHCO  ,CHSA  ,CHSD  ,CHSO  ,CHTA  ,CHTD  ,CHTO  ,CNHCA ,CNPACT
     1,CNPHC ,CNPHCA,CNPF  ,CNPO  ,CNPS  ,CNPT  ,NU1   ,NU2   ,VTBMLG
     1,IWRATE,HBA   ,HBB   ,HO    ,HA    ,KC    ,KAA   ,KHO   ,KHA
     1,CVRA  ,CVRB  ,BLAG  ,CBLDPC,CNBLDB,CNBLCA,VACMIN,VFATLG,CNACFT
     1,TDNL  ,OFFSET,CTOFF ,TMAX  ,TCNMN ,KFA   ,KFB   ,KFC   ,LNM
     1,CNHPF ,CNHPO ,CNHPS ,CNHPT ,TARE  ,DB(5)
      COMMCN  FEDTAR,TFEED ,NU3   ,ELW   ,ESW   ,FREQ  ,SBC   ,VWCON
     1,CMOIST,CONE  ,CNFATQ,TSPLUS,TSLESS,KNTA  ,KNTB  ,KNTC  ,LC
     1,LB    ,LK    ,LN    ,LP    ,LPNA  ,LPNB  ,LPNC  ,LR    ,LT
     1,LTL   ,TLO   ,GTO   ,TPL   ,TSL   ,CITX  ,CITO  ,BTW   ,BTT
     1,BTA   ,IX    ,QAFTAR,QAOTAR,QASTAR,QATTAR,QAWTAR,FEDKNT,QEATGL
     1,QEFTAR,QEGTAR,PRC   ,PRB   ,PRFAT ,VACERX,AGETAR,AGEN  ,ACO
     1,DC(7)
      COMMCN  QAW   ,QAWN  ,AAGE  ,TAVE  ,POWER ,QEATGN,QEATFN,FEDN
     1,VBLD,  POWERA,PHEOUT,PRVOUT,PRDOUT,PSVOUT,TE    ,TX    ,TEARTH
     1,TSUN  ,QATN  ,QASN  ,QAON  ,QAFN  ,ISPR  ,M     ,QTBLD ,VRATIO
     1,IVN   ,A     ,IEXF  ,IEXG  ,PHI   ,PHGROW,PGROW ,PBMRZ ,PACTX
     1,PACT  ,PHCA  ,PACTG
      COMMON  AC    ,IERG  ,ACOP  ,AFF   ,AFO   ,AFS   ,AFT   ,AHF
     1,AHO   ,AHS   ,AHT   ,ARJF  ,ARJO  ,ARJS  ,ARJT  ,AZ    ,BT
     1,CNEXFA,CNEXGA,CNMEG ,CNMEF ,CNPHIF,CNPHIG,CNTBMR,CNTDNF,CCNACT
     1,CONRDA,CONRDB,CONRDC,DTBX  ,DTFX  ,DTGX  ,DTHX  ,DTMX  ,DTSX
     1,DTSY  ,EAA   ,EAB   ,EAC   ,EEA   ,EEB   ,EEC   ,FAA   ,FAB
     1,FAC   ,GT    ,H     ,HB    ,HM    ,KRAT  ,N1S   ,N2S   ,N3S
     1,N4S   ,N5S   ,N6S   ,IDGF  ,IDGG  ,IS    ,K     ,KH    ,MACERX
     1,MBLDV ,MERF  ,MERG  ,METACT,MFAT  ,MHCPF ,MHCPG ,MMEF  ,MMEG
     1,MRAD  ,MTBMRX,PB    ,PBM   ,PBMR  ,PCARF ,PCARG ,PF    ,PFS
     1,PFTCCN,PG    ,PGB   ,PGX   ,PHCAR ,PHE   ,PHEOX ,PHEOY ,PHEX
      COMMON  PHEY  ,PHIACT,PM    ,PMEF  ,PMEG  ,PMF   ,POWERX,PRA
     1,PRAC  ,PRVCCN,PRVCX ,PRVV  ,PS    ,PSH   ,PSHX  ,PSHY  ,PSS
     1,PSV   ,PSVCON,PVV   ,PVVX  ,PX    ,PXA   ,PXB   ,PXC   ,PXD
     1,PXE   ,PXX   ,QBLD  ,QGPFED,QGRAIN,RATREF,RRADA ,RRADB ,RRADC
```

```
1,ST    ,TA    ,TBMR  ,TEA   ,TEAFOR,TEB   ,TEBFOR,TEC   ,TECFOR
1,TEF   ,TEFX  ,TELGG ,TERSIN,TESIN ,TGM   ,TGS   ,THFOR ,TL
1,TLCK  ,TLD   ,TCS   ,TOT   ,TPN   ,TPM   ,TPS   ,TPT   ,TSF
1,TSFX  ,TSLGG ,TSNSIN,TXSIN ,VACER ,VPR   ,VWCONA,WE    ,WS
1,AB    ,PVE   ,COSTG ,CNTDNG,DD(8) ,DE(60)
 COMMON AA    (05),DN    (07),MIS   ( 9),PC    ( 6),VEN   ( 9)
1      ,PVDA  (20),PVDB  (20),PVDC  (20),PVDD  (20),PVDE  (20)
1      ,PVDBTW(20),PVDBTT(20),PVDBTA(20),PVTA  ( 5),PVTB  ( 5)
1      ,PVTC  ( 5),PVTD  ( 5),PVTE  ( 5),LX    ( 6),XX    ( 6)
1      ,PICIAS( 5),PICIAT( 5),PICIAF( 5),PICIAO( 5),PICQAS( 5)
1      ,PICQAT( 5),PICQAF( 5),PICQAO( 5),PICQVF( 5),PICQVG( 5)
1      ,PICACT( 5),PICAGE( 5),PICFED( 5),PICHCO( 5),LD    ( 5)
1      ,CMD   ( 5),LTX   ( 5),CMT   ( 5),LCX   ( 5),COST  ( 5)
1      ,NP    ( 6),TDEL  ( 6),CA    (10),KA    ( 5),TC    ( 6)
1      ,TP    ( 6),TO    ( 6),TGR   ( 6),T     ( 6),N     ( 6)
 COMMON ZZ9992(7042),NALARM,IZ9993,ZZ9994(417),KEEP,ZZ9995(489)
$,IZ0000,ZZ9996(824),IZ9997,IZ9998,ZZ9999( 873)
 DIMENSION C(8000)
 EQUIVALENCE (C     ( 1),TIME  )
 EQUIVALENCE (TC    ( 1),TCG   ),(TC    ( 2),TCB   )
 EQUIVALENCE (TC    ( 3),TCM   ),(TC    ( 4),TCF   )
 EQUIVALENCE (TC    ( 5),TCS   ),(TC    ( 6),TCH   )
 EQUIVALENCE (LX    ( 1),LXA   ),(LX    ( 2),LXB   )
 EQUIVALENCE (LX    ( 3),LXC   ),(LX    ( 4),LXD   )
 EQUIVALENCE (LX    ( 5),LXE   ),(LX    ( 6),LXF   )
 EQUIVALENCE (XX    ( 1),XA    ),(XX    ( 2),XB    )
 EQUIVALENCE (XX    ( 3),XC    ),(XX    ( 4),XD    )
 EQUIVALENCE (XX    ( 5),XE    ),(XX    ( 6),XF    )
 EQUIVALENCE (LD    ( 1),LDA   ),(LD    ( 2),LDB   )
 EQUIVALENCE (LD    ( 3),LDC   ),(LD    ( 4),LDD   )
 EQUIVALENCE (LD    ( 5),LDE   )
 EQUIVALENCE (CMD   ( 1),CMDA  ),(CMD   ( 2),CMDB  )
 EQUIVALENCE (CMD   ( 3),CMDC  ),(CMD   ( 4),CMDD  )
 EQUIVALENCE (CMD   ( 5),CMDE  )
 EQUIVALENCE (LTX   ( 1),LTA   ),(LTX   ( 2),LTB   )
 EQUIVALENCE (LTX   ( 3),LTC   ),(LTX   ( 4),LTD   )
 EQUIVALENCE (LTX   ( 5),LTE   )
 EQUIVALENCE (CMT   ( 1),CMTA  ),(CMT   ( 2),CMTB  )
 EQUIVALENCE (CMT   ( 3),CMTC  ),(CMT   ( 4),CMTD  )
 EQUIVALENCE (CMT   ( 5),CMTE  )
 EQUIVALENCE (LCX   ( 1),LCA   ),(LCX   ( 2),LCB   )
 EQUIVALENCE (LCX   ( 3),LCC   ),(LCX   ( 4),LCD   )
 EQUIVALENCE (LCX   ( 5),LCE   )
 EQUIVALENCE (COST  ( 1),COSTA ),(COST  ( 2),COSTB )
 EQUIVALENCE (COST  ( 3),COSTC ),(COST  ( 4),COSTD )
 EQUIVALENCE (COST  ( 5),COSTE )
 EQUIVALENCE (N     ( 1),N1    ),(N     ( 2),N2    )
 EQUIVALENCE (N     ( 3),N3    ),(N     ( 4),N4    )
 EQUIVALENCE (N     ( 5),N5    ),(N     ( 6),N6    )
 EQUIVALENCE (NP    ( 1),NA    ),(NP    ( 2),NB    )
 EQUIVALENCE (NP    ( 3),NC    ),(NP    ( 4),ND    )
 EQUIVALENCE (NP    ( 5),NE    ),(NP    ( 6),NF    )
 EQUIVALENCE (TDEL  ( 1),TDELA ),(TDEL  ( 2),TDELB )
 EQUIVALENCE (TDEL  ( 3),TDELC ),(TDEL  ( 4),TDELD )
 EQUIVALENCE (TDEL  ( 5),TDELE ),(TDEL  ( 6),TDELF )
 INTEGER OPT
 REAL IAS,IEXF,IS,IX,IERGX
1,IAT   ,IAF   ,IAO   ,IERF  ,IERG  ,IFF   ,KO    ,KAA
1,KHC   ,KHA   ,IWRATE,IVN   ,ISPR  ,MHCPF ,MHCPG ,MMEF  ,MMEG
```

```
     1,MFAT  ,METACT,MERG  ,MERF  ,MRAD  ,K     ,KH    ,IEXG  ,IDGG
     1,IDGF  ,MBLDV ,MTBMRX,M     ,MIS   ,KA    ,MACERX
      GO TO(39995,39996,39997,39998),IZ0000
C     SYSTEM SEGMENT OF MODEL
39995 CONTINUE
      IZ9993= 959
      IZ9997=  25
      IZ9998= 562
      READ(51)ZZ9999
      IZ9901= 2220082
      IZ9902= 5020223
      IZ9903=       873
      GO TO 39999
C
C
C   INITIAL SEGMENT OF MODEL
39996 CONTINUE
      TARTIM=TARE
      CNTDNG=CTDNGA
      CCSTG=CSTGA
      TFEED=0.0
      QEATGL=0.0
      FECKNT=0.0
      TSLESS=CITO
      TSPLUS=CITO
      TE=TECRD
  600 IF (CPT .LT.1)GO TO 700
      LB=1
      BTA=PVDBTA(LB)
      BTW=PVDBTW(LB)
      BTT=PVDBTT(LB)
      IF(LR.GT.1) GO TO 610
      LPNA=LND+1
      LPNB=LNT+1
      LPNC=LNC+1
      PX=0.0
      PXA=0.0
      PXB=0.0
      PXC=0.0
      PXC=0.0
      PXE=0.0
  610 CONTINUE
      GO TO(611,612,613,614,615,616),LPN
  616      C(LXF)=XF*T(6)
  615      C(LXE)=XE*T(5)
  614      C(LXD)=XD*T(4)
  613      C(LXC)=XC*T(3)
  612      C(LXB)=XB*T(2)
  611      C(LXA)=XA*T(1)
  700 CONTINUE
      RATREF=ACTREF+OFFSET
      VBLD=RATREF
      CNMEG=(1.0-GASG-URINEG)*CONE
      CNMEF=(1.0-GASF-URINEF)*CONE
      MHCPF=1.0-CNACPF
      MHCPG=(1.0-CNACPG)
      MMEF=(1.0-HPF)
      MMEG=(1.0-HPG)
      MFAT=(1.0        )/CNFATQ
```

```
      IF(LTEMP-3)801,802,803
  803 EEA=(1.-EA)/(EA*AREAA)
  802 EEC=(1.-EC)/(EC*AREAC)
  801 EEB=(1.-EB)/(EB*AREAB)
      TEF=(491.69+9.*TE/5.)
      TELGG=ALOG(TEF)
      TEFX= (54.6329-12301.688/TEF-5.16923*TELGG)
      PVE=RHUM*EXP(TEFX)
      WE=0.6219*(PVE/(14.696-PVE))
      GO TO 39999
C
C    DYNAMIC SEGMENT OF MODEL
C
39997 CONTINUE
      IF(TIME.LE.0.) GOTO 30001
      KNTA=KNTA+1
      IF(KNTA.GE.KFA) GO TO 30001
      KNTB=KNTB+1
      IF(KNTB.GE.KFB) GO TO 30002
      KNTC=KNTC+1
      IF(KNTC.GE.KFC) GO TO 30003
      IF (KRAT.GT.0   ) GO TO 30004
      GO TO 30005
C
C     COMPUTATIONS FOR DATA SAMPLED AT INTERVALS GREATER THAN ONE DAY
C
30001 CONTINUE
      KNTA=0
      QAW=QAS+QAT+QAF+QAO
      PC(1)=QAO
      PC(2)=QAS
      PC(3)=QAT
      PC(4)=QAF
      PC(6)=QAW
      CALL TCOMP(AA,VEN,PC,DN,MIS,CA,KA,TC,A,IVN)
      IF(LTEMP-3)811,812,813
  813 AZ=CPA*A
      IF(FEA.LT.0.000001) GO TO 21
      IF( AZ.LT.0.000001) GO TO 21
      EAA=(1.-ESW)/(ESW*AZ)
      FAA=1./(AZ*FEA)
      RRADA=EAA+FAA+EEA
      CONRDA=SBC/RRADA
      GO TO 24
   21 CONRDA=0.0
   24 CONTINUE
  812 AC=CPC*A
      IF(FEC.LT.0.000001) GO TO 23
      IF( AC.LT.0.000001) GO TO 23
      EAC=(1.-ELW)/(ELW*AC)
      FAC=1./(AC*FEC)
      RRADC=EAC+FAC+EEC
      CONRDC=SBC/RRADC
      GO TO 26
   23 CONRDC=0.0
   26 CONTINUE
  811 AB=CPB*A
      IF(FEB.LT.0.000001) GO TO 22
      IF( AB.LT.0.000001) GO TO 22
```

```
      EAB=(1.-ELW)/(ELW*AB)
      FAB=1./(AB*FEB)
      RRADB=EAB+FAB+EEB
      CONRCB=SBC/RRADB
      GO TO 25
   22 CONRCB=0.0
   25 CONTINUE
      METACT = MIS(8)*QAO+MIS(4)*QAS+MIS(9)*QAT+MIS(5)*QAF
      PBMR=CNBMQ*METACT
      CBLC=QAW*CBLDPC
      MERG=ERA + QAW*(ERB+QAW*ERC)
      MERF=CNERF*MERG
      CGPFED=CFEDA+QAW*(CFEDB+QAW*CFEDC)
      PRVCX=VWCON*IVN*IWRATE
      PRVCON=CA(8)*PRVCX/A
      PSVCON=CA(9)*VWCON
      VWCONA=VWCON*A
      PFTCON=MIS(6)*CA(6)
      CNPHIG=HPG*CA(8)/A
      CNPHIF=HPF*CA(8)/A
      MRAD=CA(10)/A
      CNEXGA=(CNDIGG-CNDIGG*CNTDNG)/CNTDNG
C
C     COMPUTATIONS FOR DATA SAMPLED AT DAILY INTERVALS
C
30002 CONTINUE
      KNTB=0
      AAGE=SAGE+TIME/24.
      CNTDNF=CTDNA+AAGE*(CTDNB+AAGE*CTDNC)
      IF(AAGE.LT.RTCTIM)GOTO42
      CNTDNG=CTDNGC
      COSTG=CSTGC
      GOTO45
 42   CONTINUE
      IF(AAGE.LT.RTBTIM)GOTO45
      CNTDNG=CTDNGB
      COSTG=CSTGB
 45   CONTINUE
      IF(CNTDNF.GT.TDNL) CNTDNF=TDNL
      CNEXFA=(CNDIGF-CNDIGF*CNTDNF)/CNTDNF
      QAW=QAS+QAT+QAF+QAO
      MBLDV=CNBLDA+CNBLDB*TAVBLD
      QTBLD=MBLDV*QBLD
      AHS=CHSO+QAS*(CHSD+QAS*CHSA)
      AFS=CRN*(AHS-QAS)
      AHT=CHTO+QAS*(CHTD+QAS*CHTA)
      AFT=CRN*(AHT-QAT)
      AHF=CHFO+QAT*(CHFD+QAT*CHFA)
      AFF=CRN*(AHF-QAF)
      AHO=CHOO+QAO*(CHOD+QAO*CHOA)
      AFO=CRN*(AHO-QAO)
      QAFN=QAF-QAFTAR
      QATN=QAT-QATTAR
      QASN=QAS-QASTAR
      QAON=QAO-QAOTAR
      QAWN=QAW-QAWTAR
      AGEN=AAGE-AGETAR
C
C     COMPUTATIONS FOR DATA SAMPLED AT HOURLY INTERVALS
```

```
C
30003 CONTINUE
      KNTC=0
   30 TAVE=(TG*CA(1)+TB*CA(2)+TM*CA(3))/CA(7)
        TAVBX=(TAVE-TAVBLD) /BLAG
      IF (TAVE.LT.TCNMN) GO TO 20
      K=KO+KAA*TAVE
      KH=KHC+KHA*TAVE
      H=HC+HA*TAVE
      HB=HBA+HBB*TAVE
      HM=CMOIST*H
      VRATIO=CVRA+CVRB*TAVE
   20 CONTINUE
      IF (TS.LT.TSLESS) GO TO 18
      IF (TS.GT.TSPLUS) GO TO  18
      GO TO 19
   18 TSLESS=TS-CTOFF
      TSPLUS=TS+CTOFF
      TSF=(491.69+9.*TS/5.)
      TSLGG=ALOG(TSF)
      TSFX= (54.6329-12301.688/TSF-5.16923*TSLGG)
      PSS=EXP(TSFX)
      WS=0.6219*(PSS/(14.696-PSS))
   19 CONTINUE
      TBMR=TMIN-TAVE
      CNTBMR=0.0
      IF(TBMR.GT.0.0 )  CNTBMR=1.0
      IF(MTBMRX.GT.0.) CNTBMR=1.0
      MTBMRX=CNTBMR*VTBMRZ-CITX
      VTBMRX=TBMR*CNTBMR/VTBMLG
      PBMRZ=PBMR*(MTBMRX+1. +TBMR/VTBMLG)
      PGB=KA(1)*K*(TG-TB)
      DTGX=PGB/TCG
      PRVV=PRVCON*VRATIO
      PRVOUT=PRVCX*VRATIO
      PGX=PRVV*CA(1)
      PVVX=PBMRZ*PFTCON
      PBM=KA(2)*K*(TB-TM)
      DTBX=(PGB-PBM)/TCB
      PMF=KA(3)*K*(TM-TF)
      DTMX=(PBM-PMF)/TCM
      DTFX=(PMF-PFS)/TCF
      PSHY=KA(5)*KH
      PSHX=KA(4)*K
      M=(WS-WE)*HB*HM/(HB+HM)
      PSV=PSVCON*M
      PSVOUT=VWCONA*M
      THFOR=(TH+273.16)**4
      TESIN  =SINE(0.,FREQ  ,TEPS )
      TE=TEAMP*TESIN +TEORD
      GO TO (821,822,823,824),LTEMP
  824 TSNSIN =SINE(0.,FREQ  ,TSNPS)
      TSUN=TSNAMP*TSNSIN+TSNORD
      TEA=TSUN +273.16
      TEAFOR=TEA**4
      PRA=CONRDA*(THFOR-TEAFOR)
  823 TERSIN =SINE(0.,FREQ  ,TERPS)
      TEARTH = TERAMP*TERSIN+TERORD
      TEC=TEARTH  + 273.16
```

```
     TECFOR=TEC**4
     PRC=CONRDC*(THFOR-TECFOR)
822  TXSIN=SINE(0.0,FREQ , TXPS)
     TX=TXAMP*TXSIN+ TXORD
     GO TO 825
821  TX=TE
     TEB=TX+273.16
825  TEBFCR=TEB**4
     PRB=CONRDB*(THFOR-TEBFOR)
     PRDOUT=(PRA+PRB+PRC)
     PRAD=PRDCUT*MRAC
     PHEY=CA(10)*H*TE
     PHEX=CA(10)*H
     PHECX=A*H
     PHEOY=A*H*TE
     CTFX=PRAC/TCH
     POWERX=PRVOUT+PSVCUT+PRDOUT
     IS=ISPR
     IF(IS.LT.CITX) GO TO 911
     IF(IS.LT.IX) GO TO 911
     FECKNT=FEDKNT+1.C
911  IX=ISPR+CITX
     FEDN=FEDKNT-FEDTAR
     IF(TIME.LT.TFEED) GO TO 85
     QGRAIN=QEATGL-0.5*QGPFED
     IF (QEATG.LT.QGRAIN) GO TO  85
     QEATGL=QEATGL+QGPFED
     TFEED=TFEED+TINVL
  85 CONTINUE
     IF(TIME.LT.TARTIM) GO TO 798
     QEGTAR=QEATG
     QEFTAR=QEATF
     FECTAR=FEDKNT
     QAWTAR=QAW
     QAFTAR=QAF
     QATTAR=QAT
     QASTAR=QAS
     QACTAR=QAO
     AGETAR=AAGE
     TARTIM=TARTIM+FINTIM
798  CONTINUE
     IF (CPT.LE.0) GC TC 99
     IF(TIME.LT.BTT) GO TO 99
     IF(AAGE.LT.BTA) GO TO 99
     IF(QAW.LT.BTW) GO TC 99
     GO TO (401,402,4C3,4C4,405,406),LPNA
406  PXX=C(LDE)-PVDE(LB)
     PX=PXX*PXX*CMDE+PX
405  PXX=C(LDD)-PVDD(LB)
     PX=PXX*PXX*CMDD+PX
4C4  PXX=C(LDC)-PVDC(LB)
     PX=PXX*PXX*CMDC+PX
4C3  PXX=C(LDB)-PVDB(LB)
     PX=PXX*PXX*CMDB+PX
402  PXX=C(LDA)-PVDA(LB)
     PX=PXX*PXX*CMDA+PX
401  CONTINUE
     LB=LB+1
     BTT=PVDBTT(LB)
```

```
      BTA=PVOBTA(LB)
      BTW=PVOBTW(LB)
   99 CONTINUE
C
C     COMPUTATIONS FOR DATA THAT MAY BE SAMPLED HOURLY OR MORE OFTEN
C
30004 CONTINUE
      IF(QEATG.GE.QEATGL) GOTO 80
      IERG= MERG*ISPR
      IERF=0.0
      GO TO 90
   80 IERF= MERF*ISPR
      IERG=0.
   90 CONTINUE
      IERGX=IERG*COSTG
      IEXF=(CNEXFA+CNEXFB*ISPR)*QFAF
      IEXG=(CNEXGA+CNEXGB*ISPR)*QFAG
      IDGG=CNDIGG*QFAG
      IDGF=CNDIGF*QFAF
      IF (ISPR.GT.0.0) GO TO 851
      IF(QFAG.LT.QVG ) GO TO 853
      DQFAG=(-IDGG-IEXG)
      GO TO 854
  851 IF(IERG.LT.0.0001) GO TO 852
  853 DQFAG=(QVG-QFAG)/PLAGE
  854 IF(QFAF.LT.QVF ) GO TO 856
      DQFAF=(-IDGF-IEXF)
      GO TO 855
  856 DQFAF=(QVF-QFAF)/PLAFE
      GO TO 855
  852 DQFAF=(QVF-QFAF)/PLAFE
      IF(QFAG.LT.QVG ) GO TO 857
      DQFAG=(-IDGG-IEXG)
      GO TO 855
  857 DQFAG=(QVG-QFAG)/PLAGE
  855 CONTINUE
      DQVF=IERF-IDGF-IEXF
      DQVG=IERG-IDGG-IEXG
      PHCA=EHCAR*CNHCA
      PMEF=CNMEF*IDGF
      PCARF=MMEF*PMEF
      PMEG=CNMEG*IDGG
      PCARG=MMEG*PMEG
      PHCAR=MHCPG*PCARG+MHCPF*PCARF
      DEHC=PHCAR-PHCA
      IF(LFAT)832,832,831
  831 VACER=VACMIN-VBLD
      CONACT=0.0
      IF(VACER.GT.0.0) CONACT=1.0
      IF(MACERX.GT.0.) CONACT=1.0
      MACERX=CNACFT*VACERZ-CITX
      VACERX=CONACT*VACER
      VFATX= (VACERX-VACERZ)/VFATLG
      IF (VACERZ.LT.CITO)VACERZ=0.0
      PRFAT=METACT*MACERX
  832 CONTINUE
      PACT=CNACPG*PCARG+CNACPF*PCARF
      PGROW=IAS*CNPS+IAT*CNPT+IAF*CNPF+IAO*CNPO
      PACTG=PHCA-PGROW
```

```
      IF (PACTG.LT.0.0) GO TO 31
      PACTX=(1.0-CNPHCA)*PACTG-CNPHC*PGROW
      PHIACT=CNPHCA*PACTG+CNPHC*PGROW
      GO TO 32
   31 PACTX=(1.0+CNPACT)*PACTG-CNPHC*PHCA
      PHIACT=CNPHC*PHCA-CNPACT*PACTG
   32 CONTINUE
      DEACT=(PACTX+PACT-PBMRZ+PRFAT)
      VPR=CNVPR*VBLD-CORVPR
      ARJS=CRSO +VPR*(CRSD+VPR*CRSA)
      DIAS=ARJS*AFS-(CRN+ARJS)*IAS
      ARJT=CRTO +VPR*(CRTD+VPR*CRTA)
      DIAT=ARJT*AFT-(CRN+ARJT)*IAT
      ARJF=CRFO +VPR*(CRFD+VPR*CRFA)
      DIAF=ARJF*AFF-(CRN+ARJF)*IAF
      IFF=IAF-PRFAT*MFAT
      ARJO=CROO +VPR*(CROD+VPR*CROA)
      DIAO=ARJO*AFO-(CRN+ARJO)*IAO
      PHI=PMEG*CNPHIG+PMEF*CNPHIF
      PHGROW=PHIACT+IAS*CNHPS+IAT*CNHPT+IAF*CNHPF+IAO*CNHPO
      PVV=PHGROW*PFTCON+PVVX
      PG=(PVV+PHI)*CA(1)-PGX
      DTG=PG/TCG-DTGX
      PB=PVV*CA(2)
      DTB=PB/TCB+DTBX
      PM=PVV*CA(3)
      DTM=PM/TCM+DTMX
      PF=PVV*CA(4)
      DTF=PF/TCF +DTFX
      PS=PVV*CA(5)
      DTSX=PS/TCS
      ISPR=0.0
      IF(VBLD.LT.ACTREF)ISPR=1.0
      IF (TAVE.GT.TMAX) ISPR=0.0
      QEATGN=QEATG-QEGTAR
      QEATFN=QEATF-QEFTAR
      PHECUT=PHEOX*TH-PHEOY
      POWER=POWERX+PHECUT
      POWERA=POWER/A
C
C     COMPUTATIONS FOR DATA SAMPLED AT LESS THAN HOURLY INTERVALS
C
30005 CONTINUE
      VBLD=EACT/QTBLD
      KRAT=0.0
      IF(VBLD.LT.RATREF) KRAT=1.0
      PSH=PSHY*(TS-TH)
      PFS=PSHX*(TF-TS)
      DTS=DTSX+(PFS-PSV-PSH)/TCS
      PHE=PHEX*TH-PHEY
      DTH=(PSH-PHE)/TCH-DTHX
      ZZ0037=IAS
      ZZ0038=IAT
      ZZ0039=IAO
      GO TO 39999
C
C  TERMINAL SEGMENT OF MODEL
C
39998 CONTINUE
```

```
      IF(OPT.LE.0) GO TO 1999
      GO TO (411,412,413,414,415,416),LPNB
  416 PXX=C(LTE)-PVTE(LR)
      PX=PXX*PXX*CMTE+PX
  415 PXX=C(LTD)-PVTD(LR)
      PX=PXX*PXX*CMTD+PX
  414 PXX=C(LTC)-PVTC(LR)
      PX=PXX*PXX*CMTC+PX
  413 PXX=C(LTB)-PVTB(LR)
      PX=PXX*PXX*CMTB+PX
  412 PXX=C(LTA)-PVTA(LR)
      PX=PXX*PXX*CMTA+PX
  411 CONTINUE
      GO TO (421,422,423,424,425,426),LPNC
  426 PXE=PXE+C(LCE)
  425 PXD=PXD+C(LCD)
  424 PXC=PXC+C(LCC)
  423 PXB=PXB+C(LCB)
  422 PXA=PXA+C(LCA)
  421 CONTINUE
      IF (LR-LRR) 202,203,203
  203 LR=1
      IF(LRR.GT.1) GO TO 207
      GO TO 208
  202 LR=LR+1
  207 CONTINUE
      SIAO=PICIAO(LR)
      SQAO=PICQAO(LR)
      SIAS=PICIAS(LR)
      SQAS=PICQAS(LR)
      SIAT=PICIAT(LR)
      SQAT=PICQAT(LR)
      SIAF=PICIAF(LR)
      SQAF=PICQAF(LR)
      EHCO=PICHCO(LR)
      EACTO=PICACT(LR)
      QVGO=PICQVG(LR)
      QVFO=PICQVF(LR)
      CFEDA=PICFED(LR)
      SAGE=PICAGE(LR)
      CFAFO=QVFO
      CFAGO=QVGO
      IF (LR.GT.1) GO TO 1998
  208 GO TO (431,432,433,434,435,436),LPNC
  436 PX=PX+PXE*COSTE
  435 PX=PX+PXD*COSTD
  434 PX=PX+PXC*COSTC
  433 PX=PX+PXB*COSTB
  432 PX=PX+PXA*COSTA
  431 CONTINUE
      IF(OPT-1)1999,1070,1600
 1070 CONTINUE
 1001 FORMAT(1X,I5,1P10E10.3)
      IF(LT-1)1080,1100,1200
 1080 CONTINUE
      WRITE(70,1001)
      WRITE(70,1001)
      WRITE(70,1001)
      WRITE(70,1001)LK,PX,(T(LP),LP=1,LPN)
```

```
      DO 1085 LP=1,LPN
      TP(LP)=0.
 1085 CONTINUE
      LTL=0
      LN=0
      ACO=PX
      ACCP=PX
      TGS=0.
      LP=1
      LT=2
      GOTO 1220
 1100 CONTINUE
      IF(PX-ACO)1140,1150,1150
 1140 CONTINUE
      ACO=PX
      TLC=TL
      TLD=1.5*TLD
      GOTO 1300
 1150 CONTINUE
      TL=TLC
      TLD=-.3*TLD
      GOTO 1300
 1200 CONTINUE
      GT=(PX-ACO)/(ST+CITO)
      TGS=TGS+GT*GT
      TGR(LP)=GT
      T(LP)=TO(LP)
      LP=LP+1
      IF(LP.GT.LPN) GOTO 1250
 1220 CONTINUE
      ST=TLO*TP(LP)/100.
      IF(ABS(ST).LE.ABS(TO(LP))*TPL) ST=TPL*TO(LP)
      T(LP)=TO(LP)+ST
      GOTO 1399
 1250 CONTINUE
      TPS=0.
      BT=TGS/(GTO+CITO)
      GTO=TGS
      DO 1260 LP=1,LPN
      TPT=BT*TP(LP)-TGR(LP)
      TPS=TPS+TPT*TPT
      TP(LP)=TPT
 1260 CONTINUE
      TPN=LPN
      TGM=SQRT(TGS)/TPN
      TPM=SQRT(TPS)/TPN
      IF(LTL.NE.0) GOTO 1280
      TLO=10./(SQRT(TPS)+CITO)
      LTL=1
 1280 CONTINUE
      TLD=.1*TLO
      TLCK=SQRT(TOS/(TPS+CITO))*TSL
      IF(ABS(TLD).LE.TLCK) TLD=TLCK
      TL=0.
      TLC=0.
      LK=0
      LT=1
 1300 CONTINUE
      LC=0
```

```
      TL=TL+TLD
      DO 1310 LP=1,LPN
      TA=TO(LP)+TL*TP(LP)
      IF(ABS(TA-T(LP)).LE.ABS(T(LP))*TSL) LC=LC+1
      T(LP)=TA
 1310 CONTINUE
      IF(LC.GE.LPN) GOTO 1350
      LK=LK+1
      GOTO 1399
 1350 CONTINUE
      IF(ACO.GE.ACOP) GOTO 1370
      ACOP=ACO
      TOS=0.
      DO 1360 LP=1,LPN
      TOT=TO(LP)+TLO*TP(LP)
      TOS=TOS+TOT*TOT
      TO(LP)=TOT
      T(LP)=TOT
 1360 CONTINUE
 1370 CONTINUE
      WRITE(70,1001)LK,ACO,(TO(LP),LP=1,LPN),TLO,TGM,TPM
      IF(TLO.NE.0.) LN=0
      IF(TLO.EQ.0.) LN=LN+1
      IF(LN.GE.LNM) GOTO 1390
      TGS=0.
      LP=1
      LT=2
      GOTO 1220
 1390 CONTINUE
      LT=0
      GO TO 1999
 1399 GO TO 1998
 1600 CONTINUE
C
C       GRID SEARCH ROUTINE
C
 1601 FORMAT(1X,1PE10.3,0P6I5,5X,1P6E10.3)
 1602 FORMAT(1X,1PE10.3,0P6I5)
      WRITE(70,1601)PX,N1,N2,N3,N4,N5,N6,(T(LP),LP=1,LPN)
      IF(PX.GT.ACO) GOTO 1609
      ACO=PX
      N1S=N1
      N2S=N2
      N3S=N3
      N4S=N4
      N5S=N5
      N6S=N6
 1609 CONTINUE
      GOTO(1611,1612,1613,1614,1615,1616),LPN
 1616 CONTINUE
      N6=N6+1
      IF(N6.LT.NF) GOTO 1620
      N6=0
 1615 CONTINUE
      N5=N5+1
      IF(N5.LT.NE) GOTO 1620
      N5=0
 1614 CONTINUE
      N4=N4+1
```

```
      IF(N4.LT.ND) GOTO 1620
      N4=0
 1613 CONTINUE
      N3=N3+1
      IF(N3.LT.NC) GOTO 1620
      N3=0
 1612 CONTINUE
      N2=N2+1
      IF(N2.LT.NB) GOTO 1620
      N2=0
 1611 CONTINUE
      N1=N1+1
      IF(N1.LT.NA) GOTO 1620
      N1=0
      WRITE(70,1602)ACC,N1S,N2S,N3S,N4S,N5S,N6S
      WRITE(70,1602)
      GOTO 1999
 1620 CONTINUE
      GOTO(1631,1632,1633,1634,1635,1636),LPN
 1636 CONTINUE
      T(6)=1.+TDELF*N6
 1635 CONTINUE
      T(5)=1.+TDELE*N5
 1634 CONTINUE
      T(4)=1.+TDELD*N4
 1633 CONTINUE
      T(3)=1.+TDELC*N3
 1632 CONTINUE
      T(2)=1.+TDELB*N2
 1631 CONTINUE
      T(1)=1.+TDELA*N1
 1998 CONTINUE
      KEEP=2
 1999 CONTINUE
39999 CONTINUE
      RETURN
      END

$ENDLIST
```

APPENDIX J

WORD LIST AND DEFINITIONS

```
********                         WORD LIST                              ********

A      = AREA                                                               320
AAGE   = AGE OF ANIMAL                                                      295
AA(5)  = CONSTANTS FOR EMPIRICAL RELATIONSHIP OF AREA =F(WEIGHT)            503
AB     = ANIMAL AREA RADIATING TO ENVIRONMENT                               491
AC     = ANIMAL AREA RADIATING TO EARTH                                     331
ACO    = CURRENT OPTIMUM PERF  INDEX DURING SEARCH                          285
ACOP   = OPTIMUM PERF  INDEX FOUND ALONG LINE                               333
ACTREF = ACETATE CONCENTRATION FOR EATING CONTROL                           155
AFF    = FORCING FUNCTION FOR GROWTH OF FAT                                 334
AFO    = FORCING FUNCTION FOR GROWTH OF OFFAL                               335
AFS    = FORCING FUNCTION FOR GROWTH OF SKELETON                            336
AFT    = FORCING FUNCTION FOR GROWTH OF TISSUE                              337
AGEN   = NET VALUE OF AGE                                                   284
AGETAR = TARE VALUE OF AGE                                                  283
AHF    = HEREDITY FUNCTION FOR FAT                                          338
AHO    = HEREDITY FUNCTION FOR OFFAL                                        339
AHS    = HEREDITY FUNCTION FOR SKELETON                                     340
AHT    = HEREDITY FUNCTION FOR TISSUE                                       341
AREAA  = AREA OF SUN FOR RADIATION TRANSFER                                 134
AREAB  = AREA OF ENVIRONMENT EXCHANGING RADIATION WITH ANIMAL               120
AREAC  = AREA OF EARTH EXCHANGING RADIATION WITH ANIMAL                     127
ARJF   = MAJOR RATE FUNCTION FOR FAT                                        342
ARJO   = MAJOR RATE FUNCTION FOR OFFAL                                      343
ARJS   = MAJOR RATE FUNCTION FOR SKELETON                                   344
ARJT   = MAJOR RATE FUNCTION FOR TISSUE                                     345
AZ     = ANIMAL AREA RADIATING TO SUN                                       346
BLAG   = LAG IN BLOOD VOLUME = F(TAVBLD)                                    207
BT     = WEIGHTING FUNCTION FOR CONJ GRAD METHOD                            347
BTA    = CURRENT AGE CHECK POINT IN DYNAMIC PERF INDEX                      268
BTT    = CURRENT TIME CHECK POINT IN DYNAMIC PERF INDEX                     267
BTW    = CURRENT WEIGHT CHECK POINT IN DYNAMIC PERF INDEX                   266
CA(10) = CROSS SECTION AREA OF EQUIVALENT THERMAL CYLINDER                  545
CBLDPC = PERCENT OF BLOOD IN LIVE ANIMAL TISSUE                             208
CFEDA  = ZERO ORDER COEFF OF GRAIN FED AS FUNC OF ANIMAL WGT                090
CFEDB  = FIRST ORDER COEFF OF GRAIN FED AS FUNC OF ANIMAL WGT               091
CFEDC  = SECOND ORDER COEFF OF GRAIN FED AS FUNC OF ANIMAL WGT              092
CHFA   = SECOND ORDER COEFF IN HEREDITY FUNC FOR FAT                        173
CHFD   = FIRST  ORDER COEFF IN HEREDITY FUNC FOR FAT                        174
CHFO   = ZERO   ORDER COEFF IN HEREDITY FUNC FOR FAT                        175
CHOA   = SECOND ORDER COEFF IN HEREDITY FUNC FOR OFFAL                      176
CHOD   = FIRST  ORDER COEFF IN HEREDITY FUNC FOR OFFAL                      177
CHOO   = ZERO   ORDER COEFF IN HEREDITY FUNC FOR OFFAL                      178
CHSA   = SECOND ORDER COEFF IN HEREDITY FUNC FOR SKELETON                   179
CHSD   = FIRST  ORDER COEFF IN HEREDITY FUNC FOR SKELETON                   180
CHSO   = ZERO   ORDER COEFF IN HEREDITY FUNC FOR SKELETON                   181
CHTA   = SECOND ORDER COEFF IN HEREDITY FUNC FOR TISSUE                     182
CHTD   = FIRST  ORDER COEFF IN HEREDITY FUNC FOR TISSUE                     183
CHTO   = ZERO   ORDER COEFF IN HEREDITY FUNC FOR TISSUE                     184
CITO   = SMALL NUMBER TO AVOID DIVIDE BY ZERO ERRORS                        265
CITX   = SMALL NUMBER FOR MISC  CALCS                                       264
CMDA   = COST WEIGHTING OF PARAMETERS USED IN DYNAMIC PERF INDEX            538
```

```
CMDB   = COST WEIGHTING OF PARAMETERS USED IN DYNAMIC PERF INDEX              538
CMDC   = COST WEIGHTING OF PARAMETERS USED IN DYNAMIC PERF INDEX              538
CMDD   = COST WEIGHTING OF PARAMETERS USED IN DYNAMIC PERF INDEX              538
CMDE   = COST WEIGHTING OF PARAMETERS USED IN DYNAMIC PERF INDEX              538
CMD(5) = COST WEIGHTING OF PARAMETERS USED IN DYNAMIC PERF INDEX              538
CMOIST = CONSTANT TO CONVERT FROM H TO HM                                     241
CMTA   = COST WEIGHTING VALUES FOR PARAM USED IN TERMINAL PERF INDEX          540
CMTB   = COST WEIGHTING VALUES FOR PARAM USED IN TERMINAL PERF INDEX          540
CMTC   = COST WEIGHTING VALUES FOR PARAM USED IN TERMINAL PERF INDEX          540
CMTD   = COST WEIGHTING VALUES FOR PARAM USED IN TERMINAL PERF INDEX          540
CMTE   = COST WEIGHTING VALUES FOR PARAM USED IN TERMINAL PERF INDEX          540
CMT(5) = COST WEIGHTING VALUES FOR PARAM USED IN TERMINAL PERF INDEX          540
CNACFT = CONTROL CONSTANT FOR RATE OF CONVERSION OF POWER FROM FAT            213
CNACPF = PERCENT OF FORAGE RATION CONVERTED TO ACETATE                        109
CNACPG = PERCENT OF GRAIN RATION CONVERTED TO ACETATE                         099
CNBLDA = ZERO ORDER CONSTANT FOR BLOOD VOLUME = F(TAVBLD)                     210
CNBLDB = 1ST ORDER CONSTANT FOR BLOOD VOLUME =F(TAVBLD)                       209
CNBMQ  = MINIMUM BMR RATE                                                     087
CNDIGF = CONDUCTANCE OF FORAGE ENERGY INTO BODY                               102
CNDIGG = CONDUCTANCE OF GRAIN ENERGY INTO BODY                                094
CNERF  = RATIO OF EATING RATE FOR FORAGE TO GRAIN                             100
CNEXFA = ZERO ORDER CONSTANT FOR IEXF                                         348
CNEXFB = CONSTANT FOR TDN REDUCTION (EXCREMENT INCREASE) FOR FORAGE           159
CNEXGA = ZERO ORDER CONSTANT FOR IEXG                                         349
CNEXGB = CONSTANT FOR TDN REDUCTION (EXCREMENT INCREASE) FOR GRAIN            158
CNFATQ = CONVERSION FACTOR FROM WEIGHT OF FAT TO ENERGY                       243
CNHCA  = RELEASE RATE FOR HIGHER CARBONS                                      185
CNHPF  = HEAT INCREMENT OF FAT SYNTHESIS                                      223
CNHPO  = HEAT INCREMENT OF OFFAL SYNTHESIS                                    224
CNHPS  = HEAT INCREMENT OF SKELETON SYNTHESIS                                 225
CNHPT  = HEAT INCREMENT OF TISSUE SYNTHESIS                                   226
CNMEF  = CONVERT FORAGE DIGESTION RATE TO POWER                               351
CNMEG  = CONVERT GRAIN DIGESTION RATE TO POWER                                350
CNPACT = INEFFICIENCY OF ACETATE FOR GROWTH                                   186
CNPF   = CONSTANT FOR ENERGY DENSITY REQUIRED FOR FAT PRODUCTION              189
CNPHC  = PERCENT OF POWER LOST (HEAT) FOR CONVERSION OF HIGH CAR  TO GROWTH   187
CNPHCA = PERCENT OF POWER LOST (HEAT) FOR CONVERSION OF HIGH CAR TO ACETATE   188
CNPHIF = HEAT INCREMENT OF FORAGE--ADJUSTED TO THERMAL CYLINDER               352
CNPHIG = HEAT INCREMENT OF GRAIN--ADJUSTED TO THERMAL CYLINDER                353
CNPO   = CONSTANT FOR ENERGY DENSITY REQUIRED FOR OFFAL PRODUCTION            190
CNPS   = CONSTANT FOR ENERGY DENSITY REQUIRED FOR SKELETON PRODUCTION         191
CNPT   = CONSTANT FOR ENERGY DENSITY REQUIRED FOR TISSUE PRODUCTION           192
CNTBMR = CONSTANT TO ADJUST CONTROL RATE OF BMR                               354
CNTDNF = TDN OF FORAGE RATION                                                 355
CNTDNG = INTERNAL VALUE OF TDN OF GRAIN                                       494
CNVPR  = CONSTANT TO ADJUST BLOOD ACETATE LEVEL TO GROWTH DESIRED             157
CONACT = CONTROL FOR ERROR SIGNAL FOR POWER FROM FAT                          356
CONE   = CONVERSION OF DIGESTED ENERGY TO CALORIES                            242
CONRDA = RADIATION TRANSFER COEFFICIENT, ANIMAL AND SUN                       357
CONRDB = RADIATION TRANSFER COEFFICIENT, ANIMAL AND ENVIRONMENT               358
CONRDC = RADIATION TRANSFER COEFFICIENT, ANIMAL AND EARTH                     359
CORVPR =  ORDINATE ADJUSTMENT FOR VPR FUNCTION                                156
COSTA  = COST OF PARAM USED IN COST SECTION OF PERFORM INDEX                  542
COSTB  = COST OF PARAM USED IN COST SECTION OF PERFORM INDEX                  542
```

COSTC = COST OF PARAM USED IN COST SECTI~~ON OF PERFORM INDEX~~ 542
COSTD = COST OF PARAM USED IN COST SECTION OF PERFORM INDEX 542
COSTE = COST OF PARAM USED IN COST SECTION OF PERFORM INDEX 542
COSTG = INTERNAL VALUE OF COST OF GRAIN BEING EATEN 493
COST(6)= COST OF PARAM USED IN COST SECTION OF PERFORM INDEX 542
CPA = PERCENT OF ANIMAL AREA EXCHANGING RADIATION WITH SUN 131
CPB = PERCENT OF ANIMAL AREA EXCHANGING RADIATION WITH ENVIRONMENT 117
CPC = PERCENT OF ANIMAL AREA EXCHANGING RADIATION WITH EARTH 124
CRFA = SECOND ORDER COEFF IN RATE FUNC FOR FAT 161
CRFD = FIRST ORDER COEFF IN RATE FUNC FOR FAT 162
CRFO = ZERO ORDER COEFF IN RATE FUNC FOR FAT 163
CRN = TIME CONSTANT FOR GROWTH RATE CHANGES 160
CROA = SECOND ORDER COEFF IN RATE FUNC FOR OFFAL 164
CROD = FIRST ORDER COEFF IN RATE FUNC FOR OFFAL 165
CROO = ZERO ORCER COEFF IN RATE FUNC FOR OFFAL 166
CRSA = SECOND ORDER COEFF IN RATE FUNC FOR SKELETON 167
CRSD = FIRST ORDER COEFF IN RATE FUNC FOR SKELETON 168
CRSO = ZERO ORDER COEFF IN RATE FUNC FOR SKELETCN 169
CRTA = SECOND ORDER COEFF IN RATE FUNC FOR TISSUE 170
CRTD = FIRST ORDER COEFF IN RATE FUNC FOR TISSUE 171
CRTO = ZERO ORDER COEFF IN RATE FUNC FOR TISSUE 172
CSTGA = COST OF STARTER RATION 147
CSTGB = COST OF INTERMEDIATE RATION 148
CSTGC = COST OF FINISHING RATION 149
CTDNA = ZERO ORDER COEFF OF TDN OF FORAGE FED AS FUNC OF ANIM AGE 103
CTDNB = FIRST ORDER COEFF OF TDN OF FORAGE FED AS FUNC OF ANIM AGE 104
CTDNC = SECOND ORDER COEFF OF TDN OF FORAGE FED AS FUNC OF ANIM AGE 105
CTDNGA = TDN OF STARTER RATION 142
CTDNGB = TDN OF INTERMEDIATE RATION 143
CTDNGC = TDN OF FINISHING RATION 144
CTOFF = SMALL DELTA TO PROVIDE TEMPERATURE DEAD ZONE 216
CVRA = ZERO ORDER CONSTANT FOR VENT RATIO = F(TAVE) 205
CVRB = 1ST ORDER CONSTANT FOR VENT RATIO = F(TAVE) 206
DA(1) = NOT USED 150
DA(2) = NOT USED 151
DB(1-5) = NOT USED 228-232
DC(1-7) = NOT USED 286-292
DD(1-8) = NOT USED 495-502
DEACT = DERIVATIVE OF ACETATE LEVEL (INTGRL IN) 043
DE(1-60) = INDIRECT ADDRESS TABLE FOR VECTORS 503-562
DEHC = DERIVATIVE OF HIGHER CARBON POTENTIAL (INTGRL IN) 044
DF = NOT USED 095
DIAF = DERIVATIVE OF FAT GROWTH RATE (INTGRL IN) 047
DIAO = DERIVATIVE OF OFFAL GROWTH RATE (INTGRL IN) 048
DIAS = DERIVATIVE OF SKELETCN GROWTH RATE (INTGRL IN) 049
DIAT = DERIVATIVE OF TISSUE GROWTH RATE (INTGRL IN) 050
DN( ) = DENSITY OF COMPONENTS 504
DQFAF = DERIVATIVE OF FORAGE AVAIL FOR CONDUCTANCE INTO BODY (INTGRL IN) 042
DQFAG = DERIVATIVE OF GRAIN AVAIL FOR CONDUCTANCE INTO BODY (INTGRL IN) 041
DQVF = DERIVATIVE OF FORAGE EATEN (INTGRL IN) 045
DQVG = DERIVATIVE OF GRAIN EATEN (INTGRL IN) 046
DTB = DERIVATIVE OF TEMPERATURE OF BONE (INTGRL IN) 051
DTBX = HOUR DERIVATIVE VALUE OF POWER IN BONE 360
DTF = DERIVATIVE OF TEMPERATURE OF FAT (INTGRL IN) 052

```
DTFX   = HOUR DERIVATIVE VALUE OF POWER IN FAT                                361
DTG    = DERIVATIVE OF TEMPERATURE OF GASTROINTESTINAL TRACT   (INTGRL IN)   034
DTGX   = HOUR DERIVATIVE VALUE OF POWER IN GASTROINTESTINAL TRACT             362
DTH    = DERIVATIVE OF TEMPERATURE OF HAIR                     (INTGRL IN)   036
DTHX   = HOUR DERIVATIVE VALUE OF POWER IN HAIR                               363
DTM    = DERIVATIVE OF TEMPERATURE OF MEAT                     (INTGRL IN)   053
DTMX   = HOUR DERIVATIVE VALUE OF POWER IN MEAT                               364
DTS    = DERIVATIVE OF TEMPERATURE OF SKIN                     (INTGRL IN)   035
DTSX   = DERIVATIVE VALUE FOR POWER CREATED IN SKIN                           365
DTSY   = NOT USED                                                             366
EA     = REFLECTIVITY FOR SUN                                                 131
EAA    = RESISTANCE TO SHORTWAVE RADIATION BY ANIMAL REFLECTIVITY             367
EAB    = RESISTANCE TO RADIATION, ANIMAL REFLECTIVITY, LONG WAVE              368
EAC    = RESISTANCE TO RADIATION, ANIMAL REFLECTIVITY, LONG WAVE              369
EACT   = POTENTIAL OF ACETATE SUPPLY AVAILABLE FOR GROWTH                     018
EACTO  = INCON  FOR ACETATE AVAILABLE FOR GROWTH               (INTGRL IC)   068
EB     = REFLECTIVITY FOR ENVIRONMENT                                         119
EC     = REFLECTIVITY FOR EARTH                                               126
EEA    = RESISTANCE TO RADIATION, REFLECTIVITY OF SUN                         370
EEB    = RESISTANCE TO RADIATION, REFLECTIVITY OF ENVIRONMENT                 371
EEC    = RESISTANCE TO RADIATION, REFLECTIVITY OF EARTH                       372
EHCAR  = POTENTIAL OF HIGHER CARBONS AVAILABLE                 (INTGRL OUT)  019
EHCO   = INCON  FOR ENERGY FROM HIGHER CARBONS                 (INTGRL IC)   069
ELW    = REFLECTIVITY OF ANIMAL TO LONG WAVE RADIATION                        236
ERA    = ZERO ORDER COEFF OF EATING RATE AS FUNC OF ANIM WGT                  152
ERB    = FIRST ORDER COEFF OF EATING RATE AS FUNC OF ANIM WGT                 153
ERC    = SECOND ORDER COEFF OF EATING RATE AS FUNC OF ANIM WGT                154
ESW    = REFLECTIVITY OF ANIMAL TO SHORTWAVE RADIATION                        237
FAA    = RESISTANCE TO RADIATION,VIEW FACTOR, ANIMAL TO SUN                   373
FAB    = RESISTANCE TO RADIATION,VIEW FACTOR, ANIMAL TO ENVIRONMENT           374
FAC    = RESISTANCE TO RADIATION,VIEW FACTOR, ANIMAL TO EARTH                 375
FEA    = VIEW FACTOR, ANIMAL TO SUN                                           132
FEB    = VIEW FACTOR, ANIMAL TO ENVIRONMENT                                   118
FEC    = VIEW FACTOR, ANIMAL TO EARTH                                         125
FEDKNT = NUMBER OF TIMES ANIMAL HAS EATEN                                     275
FEDN   = NET NUMBER OF TIMES ANIMAL HAS EATEN                                 300
FEDTAR = TARE OF FEDKNT                                                       233
FREQ   = FREQUENCY OF ENVIROMENTAL TEMPERATURE VARIATION                      238
GASF   = PERCENT OF FORAGE ENERGY LOST AS GAS                                 107
GASG   = PERCENT OF GRAIN ENERGY LOST AS GAS                                  097
GT     = TEMPORARY CALC OF GRADIENT                                           376
GTO    = OLD VALUE OF GRADIENT MAGNITUDE SQUARED                              261
H      = SURFACE HEAT TRANSFER COEFFICIENT                                    377
HA     = 1ST  ORDER CONSTANT FOR HEAT TRANSFER COEFFICIENT                    200
HB     = BODY MOISTURE TRANSFER COEFFICIENT                                   378
HBA    = ZERO ORDER CONSTANT FOR MOISTURE CONTROL BY BODY                     197
HBB    = 1ST  ORDER CONSTANT FOR MOISTURE CONTROL BY BODY                     198
HM     = CONDUCTANCE VALUE OF MOISTURE FROM BODY                              379
HO     = ZERO ORDER CONSTANT FOR HEAT TRANSFER COEFFICIENT                    199
HPF    = PERCENT OF FORAGE LOST AS HEAT DURING DIGESTION                      108
HPG    = PERCENT OF GRAIN LOST AS HEAT DURING DIGESTION                       098
IAF    = GROWTH RATE OF ANIMAL FAT                             (INTGRL OUT)  022
IAO    = GROWTH RATE OF OFFAL                                  (INTGRL OUT)  023
IAS    = GROWTH RATE OF ANIMAL SKELETON                        (INTGRL OUT)  024
```

```
IAT    = GROWTH RATE OF ANIMAL TISSUE                           (INTGRL OUT)  025
IDGF   = FLOW RATE OF DIGESTED FORAGE                                         387
IDGG   = FLOW RATE OF DIGESTED GRAIN                                          388
IERF   = EATING RATE OF FORAGE                                  (INTGRL IN)   033
IERG   = EATING RATE OF GRAIN                                                 332
IERGX  = RATE OF VALUE OF GRAIN                                 (INTGRL IN)   032
IEXF   = EXCREMENT FRACTION OF FORAGE RATION                                  321
IEXG   = EXCREMENT FRACTION OF GRAIN RATION                                   322
IFF    = GROWTH RATE OF FAT ADJUSTED FOR THE POWER OF FAT USED (INTGRL IN)    037
IS     = INTERNAL VARIABLE TO COUNT NUMBER OF EATING PERIODS                  389
ISPR   = INSPIRATION TO EAT                                                   315
IVN    = BASE VENTILATION RATE OF ANIMAL =F(QAW)                              319
IWRATE = RATE OF VAPOR PICKUP PER LITER OF AIR                                196
IX     = INTERNAL VARIABLE FOR COUNTING NUMBER OF EATING PERIODS              269
K      = HEAT CONDUCTIVITY OF BODY                                            390
KAA    = 1ST  ORDER CONSTANT FOR HEAT CONDUCTANCE IN BODY                     202
KA(5)  = DISTANCE AND SIZE RELATIONSHIPS FOR EQUIVALENT THERMAL CYLINDER      546
KFA    = LIMIT OF COUNTER BEFORE GREATER THAN DAY SECTION UPDATE             -219
KFB    = VALUE OF COUNTER FOR DAILY UPDATE                                   -220
KFC    = VALUE OF COUNTER FOR HOURLY UPDATE                                  -221
KH     = CONDUCTANCE OF HEAT INTO HAIR                                        391
KHA    = 1ST  ORDER CONSTANT FOR HEAT CONDUCTANCE TO HAIR                     204
KHO    = ZERO ORDER CONSTANT FOR HEAT CONDUCTANCE TO HAIR                     203
KNTA   = INTERNAL VARIABLE FOR INTEGRATION CONTROL                           -246
KNTB   = INTERNAL VARIABLE FOR INTEGRATION CONTROL                           -247
KNTC   = INTERNAL VARIABLE FOR INTEGRATION CONTROL                           -248
KO     = ZERO ORDER CONSTANT FOR HEAT CONDUCTANCE IN BODY                     201
KRAT   = LOGIC SWITCH FOR INTEGRATION CONTROL                                -380
LB     = INDEX OF CURRENT DATA POINT IN DYNAMIC PERF  INDEX                  -250
LC     = COUNTER  TO INDICATE OPTIM ALONG LINE FOUND                         -249
LCA    = INDENTIFICATION OF PARAM USED IN COST SECTION OF PERF INDEX          541
LCB    = INDENTIFICATION OF PARAM USED IN COST SECTION OF PERF INDEX          541
LCC    = INDENTIFICATION OF PARAM USED IN COST SECTION OF PERF INDEX          541
LCD    = INDENTIFICATION OF PARAM USED IN COST SECTION OF PERF INDEX          541
LCE    = INDENTIFICATION OF PARAM USED IN COST SECTION OF PERF INDEX          541
LCX(5) = INDENTIFICATION OF PARAM USED IN COST SECTION OF PERF INDEX          541
LDA    = INDENTIFICATION OF PARAM USED IN DYNAMIC PERF INDEX                  537
LDB    = INDENTIFICATION OF PARAM USED IN DYNAMIC PERF INDEX                  537
LDC    = INDENTIFICATION OF PARAM USED IN DYNAMIC PERF INDEX                  537
LDD    = INDENTIFICATION OF PARAM USED IN DYNAMIC PERF INDEX                  537
LDE    = INDENTIFICATION OF PARAM USED IN DYNAMIC PERF INDEX                  537
LD(5)  = INDENTIFICATION OF PARAM USED IN DYNAMIC PERF INDEX                  537
LFAT   = SWITCH FOR POWER FROM FAT; 1= ON, 0 = OFF                           -085
LK     = COUNT OF NUMBER OF STEPS ALONG LINE IN OPTIMIZATION                 -251
LN     = COUNTER TO INDICATE COMPLETION OF OPTIMIZATION                      -252
LNC    = NUMBER OF VARIABLES IN COST PORTION OF PERFORMANCE INDEX            -138
LND    = NUMBER OF VARIABLES IN DYNAMIC PORTION OF PERFORMANCE INDEX         -139
LNM    = MINIMUM NUMBER OF ATTEMPS TO SEEK A BETTER OPTIM                    -222
LNT    = NUMBER OF VARIABLES IN TERMINAL PORTION OF PERFORMANCE INDEX        -140
LP     = PARAMETER MULTIPLIER INDEX IN OPTIMIZATION                          -253
LPN    = NUMBER OF PARAMETERS IN OPTIMIZATION OR GRID SEARCH                 -137
LPNA   = INTERNAL VARIABLE FOR NUMBER OF VAR  IN DYNAM PERF INDEX            -254
LPNB   = INTERNAL VARIABLE FOR NUMBER OF VAR  IN TERMINAL PERF INDEX         -255
LPNC   = INTERNAL VARIABLE FOR NUMBER OF VAR  IN COST PERF INDEX             -256
```

```
LR     = INTERNAL VARIABLE FOR SUBRUN NUMBER                                -257
LRR    = NUMBER OF SUBRUNS PER GRID SEARCH OR OPTIM  RUN                    -134
LT     = INTERNAL VARIABLE FOR OPTIMIZATION RUN TYPE (INIT,BASE,PERT)       -258
LTA    = INDENTIFICATION OF VALUES  OR PARAM USED FOR TERMINAL PERF INDEX    539
LTB    = INDENTIFICATION OF VALUES  OR PARAM USED FOR TERMINAL PERF INDEX    539
LTC    = INDENTIFICATION OF VALUES  OR PARAM USED FOR TERMINAL PERF INDEX    539
LTD    = INDENTIFICATION OF VALUES  OR PARAM USED FOR TERMINAL PERF INDEX    539
LTE    = INDENTIFICATION OF VALUES  OR PARAM USED FOR TERMINAL PERF INDEX    539
LTEMP  = NUMBER OF RADIATION SINKS                                          -084
LTL    = INTERNAL VARIABLE INDICATING FIRST SEARCH ALCNG LINE               -259
LTX(5) = INDENTIFICATION OF VALUES  OR PARAM USED FOR TERMINAL PERF INDEX    539
LXA    = IDENTIFICATION VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
LXB    = IDENTIFICATION VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
LXC    = IDENTIFICATION VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
LXD    = IDENTIFICATICN VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
LXE    = IDENTIFICATION VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
LXF    = IDENTIFICATION VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
LX(6)  = IDENTIFICATION VECTOR FOR  PARAM TO BE OPTIMIZED                   -521
M      = MOISTURE                                                            316
MACERX = STATUS OF DEMAND FOR POWER FROM FAT                                 392
MBLDV  = MULTIPLIER FOR BLOOD VOLUME                                         393
MERF   = MULTIPLIER FOR EATING RATE OF FORAGE =F(QAW)                        394
MERG   = MULTIPLIER FOR EATING RATE OF GRAIN=F(QAW)                          395
METACT = METABOLIC ACTIVE TISSUE                                             396
MFAT   = MULTIPLIER FOR CONVERT POWER FROM FAT TO WEIGHT                     397
MHCPF  = MULTIPLILER FOR HIGHER CARBON PERCENT FRCM FORAGE                   398
MHCPG  = MULTIPLILER FOR HIGHER CARBON PERCENT FRCM GRAIN                    399
MIS(9) = MISCELLANEOUS CONSTANTS                                             505
MMEF   = PERCENT OF FORAGE ENERGY APPEARING AS CARBON                        400
MMEG   = PERCENT OF GRAIN ENERGY APPEARING AS CARBON                         401
MRAD   = CONVERSION FACTOR FOR RADIATION TO EQUIVALENT THERMAL CYLINDER      402
MTBMRX = STATUS OF BMR CONTROL                                               403
N1     = STORAGE FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                    552
N2     = STORAGE  FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                   552
N3     = STORAGE  FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                   552
N4     = STORAGE FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                    552
N5     = STORAGE FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                    552
N6     = STORAGE FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                    552
N1S    = STORAGE OF COUNT AT OPTIMUM PERF INDEX IN GRID SEARCH              -381
N2S    = STORAGE OF COUNT AT OPTIMUM PERF INDEX IN GRID SEARCH              -382
N3S    = STORAGE OF COUNT AT OPTIMUM PERF INDEX IN GRID SEARCH              -383
N4S    = STORAGE OF COUNT AT OPTIMUM PERF INDEX IN GRID SEARCH              -384
N5S    = STORAGE OF COUNT AT OPTIMUM PERF INDEX IN GRID SEARCH              -385
N6S    = STORAGE OF COUNT AT OPTIMUM PERF INDEX IN GRID SEARCH              -386
NA     = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
NB     = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
NC     = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
ND     = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
NE     = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
NF     = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
N(6)   = STORAGE FOR NUMBER OF STEPS TAKEN IN GRID SEARCH                    552
NPCRD  = NUMBER OF PARAMETER DATA CARDS TO FOLLOW END                       -082
NP(6)  = NUMBER OF PARAM STEPS TO BE TAKEN DURING GRID SEARCH                543
NU1    = NOT USED                                                            193
```

```
NU2     = NOT USED                                                             194
NU3     = NOT USED                                                             235
NVEC    = NUMBER OF VECTORS TO LOAD FOLLOWING PARAM CARDS                     -083
OFFSET  = OFFSET USED TO START FASTER INTEGRATION BEFORE EATING STARTS         215
OPT     = TYPE OF RUN: 0-SINGLE, 1-CONJ GRAD OPTIM, 2-GRID SEARCH             -135
PACT    = POWER OF ACETATE (INPUT)                                             328
PACTG   = POWER FOR GROWING FROM ACETATE POOL                                  330
PACTX   = UNKNOWN POWER REQUIRED OF ACETATE FOR GROWTH                         327
PB      = POWER CREATED IN BONE                                                404
PBM     = POWER FLOW FROM BONE TO MEAT                                         405
PBMR    = POWER OF BASAL METABOLIC RATE                                        406
PBMRO   = INCON FOR BMR CONTROLLER                               (INTGRL IC)   079
PBMRZ   = POWER OF BMR, ADJUSTED TO ENVIRONMENT                                326
PCARF   = POWER OF CARBON ENERGY FROM FORAGE                                   407
PCARG   = POWER OF CARBON ENERGY FOR GRAIN                                     408
PC(6)   = PERCENT  OF ANIMAL BODY COMPONENTS                                   506
PF      = THERMAL POWER CREATED IN FAT                                         409
PFS     = THERMAL POWER FROM FAT TO SKIN                                       410
PFTCON  = CONVERSION FACTOR FOR POWER ADDED TO BODY, LIKE FAT POWER            411
PG      = POWER CREATED IN GASTROINTESTINAL TRACT                              412
PGB     = POWER FLOW FROM GASTROINTESTINAL TRACT TO BONE                       413
PGROW   = POWER REQUIRED TO GROW                                               325
PGX     = HOUR VAR OF RESPIRATORY VAPOR POWER IN GASTROINTESTINAL TRACT        414
PHCA    = POWER FROM HIGHER CARBONS AVAILABLE                                  329
PHCAR   = POWER OF HIGHER CARBONS (INPUT)                                      415
PHE     = THERMAL POWER FLOW FROM HAIR TO ENVIRONMENT                          416
PHEOUT  = THERMAL ENERGY LOST BY CONVECTION FROM HAIR TO ENVIRONMENT           303
PHEOX   = HOUR VARIABLE FOR CONVECTIVE HEAT TRANSFERRED OUT                    417
PHEOY   = HOUR VARIABLE FOR CONVECTIVE HEAT TRANSFERRED OUT                    418
PHEX    = HOUR VAR FOR CONVECTIVE HEAT TRANSFER (THERMAL CYLINDER)             419
PHEY    = HOUR VAR FOR CONVECTIVE HEAT TRANSFER (THERMAL CYLINDER)             420
PHGROW  = HEAT INCREMENT OF GROWTH                                             324
PHI     = HEAT INCREMENT OF DIGESTION                                          323
PHIACT  = POWER OF ACETATE CONVERTED TO HEAT                                   421
PHSY    = HOUR VARIABLE FOR POWER CONDUCTANCE INTO SKIN                        435
PICACT(05) = INCON FOR ACETATE LEVEL IN BLOOD DURING OPT                       533
PICAGE(05) = INCON FOR AGE DURING OPT                                          534
PICFED(05) = LIMITS PER FEEDING DURING OPT SECTION OF PROGRAM                  535
PICHCO(05) = INCON FOR HIGHER CARBON DURING OPT                                536
PICIAF(05) = INCON FOR FAT GAIN DURING OPT                                     525
PICIAO(05) = INCON FOR OFFAL GAIN DURING OPT                                   526
PICIAS(05) = INCON FOR SKELETON GAIN DURING OPT                                523
PICIAT(05) = INCON FOR TISSUE GAIN DURING OPT                                  524
PICQAF(05) = INCON FOR FAT DURING OPT                                          529
PICQAO(05) = INCON FOR OFFAL WEIGHT DURING OPT                                 530
PICQAS(05) = INCON FOR SKELETON WEIGHT DURING OPT                              527
PICQAT(05) = INCON FOR TISSUE WEIGHT DURING OPT                                528
PICQVF(05) = INCON FOR FORAGE IN STOMACH DURING OPT                            531
PICQVG(05) = INCON FOR GRAIN IN RUMEN DURING OPT                               532
PLAFE   = LAG OF FORAGE AVAILABILITY FOR DIGESTION                             101
PLAGE   = LAG OF GRAIN AVAILABILITY FOR DIGESTION                              093
PM      = POWER CREATED IN MEAT                                                422
PMEF    = METABOLIZABLE POWER OF FORAGE (INCLUDES HEAT INCREMENT)              423
PMEG    = METABOLIZABLE POWER OF GRAIN (INCLUDES HEAT INCREMENT OF DIG )       424
```

```
PMF     = THERMAL POWER FROM HEAT TO FAT                                           425
POWER   = THERMAL ENERGY LOSS AS HEAT (TOTAL)                                      297
POWERA  = THERMAL ENERGY LOST AS HEAT (TOTAL PER UNIT AREA)                        302
POWERX  = HOUR CALC OF POWER                                                       426
PRA     = POWER RADIATED BETWEEN ANIMAL AND SUN                                    427
PRAD    = POWER TRANSFERRED BY RADIATION EXCHANGE                                  428
PRB     = POWER RADIATED BETWEEN ANIMAL AND ENVIRONMENT                            280
PRC     = POWER RADIATED BETWEEN ANIMAL AND EARTH                                  279
PRDOUT  = THERMAL ENERGY LOST AS RADIATION                                         305
PRFAT   = POWER FROM FAT USED FOR METABOLISM                                       281
PRVCON  = CONVERSION FACTOR FOR RESPIRATORY HEAT LOSSES                            429
PRVCX   = HOUR VARIABLE FOR RESIPRATION HEAT LOSS                                  430
PRVOUT  = THERMAL ENERGY LOST AS RESPIRATION VAPOR                                 304
PRVV    = THERMAL POWER REMOVED BY VENTILATION                                     431
PS      = THERMAL POWER CREATED IN SKIN                                            432
PSH     = POWER FLOW FROM SKIN TO HAIR                                             433
PSHX    = HOUR VARIABLE FOR POWER CONDUCTANCE INTO HAIR                            434
PSS     = VAPOR PRESSURE OF SKIN, SATURATED                                        436
PSV     = THERMAL POWER LOST BY VAPORIZATION                                       437
PSVCON  = CONVERSION FACTOR FOR SKIN VAPOR HEAT LOSSES                             438
PSVOUT  = THERMAL ENERGY LOST FROM SKIN VAPORIZATION                               306
PVDA(20) = DESIRED VALUES FOR DYNAMIC PORTION OF PERFORM INDEX                     508
PVDB(20) = DESIRED VALUES FOR DYNAMIC PORTION OF PERFORM INDEX                     509
PVDBTA(20) = DESIRED AGE     AT WHICH DYN PERF INDEX IS CALCULATED                 515
PVDBTT(20) = DESIRED TIMES   AT WHICH DYN PERF INDEX IS CALCULATED                 514
PVDBTW(20) = DESIRED WEIGHTS AT WHICH DYN PERF INDEX IS CALCULATED                 513
PVDC(20) = DESIRED VALUES FOR DYNAMIC PORTION OF PERFORM INDEX                     510
PVDD(20) = DESIRED VALUES FOR DYNAMIC PORTION OF PERFORM INDEX                     511
PVDE(20) = DESIRED VALUES FOR DYNAMIC PORTION OF PERFORM INDEX                     512
PVE     = VAPOR PRESSURE OF ENVIRONMENT                                            492
PVTA(5) = DESIRED VALUE FOR FIRST  FACTOR IN TERMINAL PERFORM INDEX                516
PVTB(5) = DESIRED VALUE FOR SECOND FACTOR IN TERMINAL PERFORM INDEX                517
PVTC(5) = DESIRED VALUE FOR THIRD  FACTOR IN TERMINAL PERFORM INDEX                518
PVTD(5) = DESIRED VALUE FOR FOURTH FACTOR IN TERMINAL PERFORM INDEX                519
PVTE(5) = DESIRED VALUE FOR FIFTH FACTOR IN TERMINAL PERFORM INDEX                 520
PVV     = THERMAL POWER PER VOLUME--ADJUSTED TO THERMAL CYLINDER                   439
PVVX    = HOUR VAR FOR PVV                                                         440
PX      = PERFORMANCE INDEX                                                        441
PXA     = SUMMING AREA FOR COST PERF VARIABLE                                      442
PXB     = SUMMING AREA FOR COST PERF VARIABLE                                      443
PXC     = SUMMING AREA FOR COST PERF VARIABLE                                      444
PXD     = SUMMING AREA FOR COST PERF VARIABLE                                      445
PXE     = SUMMING AREA FOR COST PERF VARIABLE                                      446
PXX     = TEMPORARY STORAGE OF ERROR IN TERMINAL PERF INDEX CALC                   447
QAF     = WEIGHT OF FAT IN ANIMAL                                   (INTGRL OUT)  012
QAFN    = NET VALUE OF QAF                                                         314
QAFTAR  = TARE VALUE OF QAF                                                        270
QAO     = WEIGHT OF OFFAL IN ANIMAL                                 (INTGRL OUT)  013
QAON    = NET VALUE OF QAO                                                         313
QAOTAR  = TARE VALUE OF QAO                                                        271
QAS     = WEIGHT OF SKELETON IN ANIMAL                              (INTGRL OUT)  014
QASN    = NET VALUE OF QAS                                                         312
QASTAR  = TARE VALUE OF QAS                                                        272
QAT     = WEIGHT OF TISSUE IN ANIMAL                                (INTGRL OUT)  015
```

```
QATN   = NET VALUE OF QAT                                                      311
QATTAR = TARE VALUE OF QAT                                                     273
QAW    = TOTAL ANIMAL WEIGHT                                                   293
QAWN   = NET VALUE OF QAW                                                      294
QAWTAR = TARE VALUE OF QAW                                                     274
QBLD   = QUANTITY OF BLOOD AS F(QAW)                                           448
QEATF  = WEIGHT OF FORAGE EATEN                               (INTGRL OUT)     008
QEATFN = NET VALUE OF QEATF                                                    299
QEATFO = INCON  FOR FORAGE EATEN                              (INTGRL IC)      058
QEATG  = VALUE OF GRAIN EATEN                                 (INTGRL OUT)     007
QEATGL = LIMIT ON QUANTITY OF GRIAN EATEN                                      276
QEATGN = NET VALUE OF QEATG                                                    298
QEATGO = INCON  FOR GRAIN EATEN                               (INTGRL IC)      057
QEFTAR = TARE VALUE OF AMOUNT OF FORAGE EATEN                                  277
QEGTAR = TARE VALUE OF VALUE OF GRAIN EATEN                                    278
QFAF   = WEIGHT OF FORAGE AVAILABLE FOR CONDUCTANCE INTO BODY (INTGRL OUT)     017
QFAFO  = FORAGE AVAILABLE AS FATTY ACIDS FOR ABSORBTION       (INTGRL IC)      067
QFAG   = WEIGHT OF GRAIN AVAILABLE FOR CONDUCTANCE INTO BODY  (INTGRL OUT)     016
QFAGO  = GRAIN AVAILABLE FOR ABSORBTION AS FATTY ACIDS        (INTGRL IC)      066
QGPFED = QUANTITY OF GRAIN PER FEEDING                                         449
QGRAIN =  GRAIN CHECK TO DETERMINE AMOUNT EATEN                                450
QTBLD  = QUANTITY OF BLOOD AS F(QAW,TEMP)                                      317
QVF    = WEIGHT OF TDN FROM FORAGE IN STOMACH                 (INTGRL OUT)     020
QVFO   = FORAGE TDN IN STOMACH                                (INTGRL IC)      070
QVG    = WEIGHT OF TDN FROM GRAIN IN STOMACH                  (INTGRL OUT)     021
QVGO   = INCON FOR GRAIN IN RUMEN                                              071
RATREF = SWITCHING LEVEL FOR INTEGRATION CONTROL                               451
RHUM   = RELATIVE HUMIDITY                                                     110
RRADA  = RADIANT POWER TRANSFER, ANIMAL AND SUN                                452
RRADB  = RADIANT POWER TRANSFER, ANIMAL AND ENVIRONMENT                        453
RRADC  = RADIANT POWER TRANSFER, ANIMAL AND EARTH                              454
RTBTIM = TIME TO SWITCH TO INTERMEDIATE RATION                                 145
RTCTIM = TIME TO SWITCH TO FINISHING RATION                                    146
SAGE   = INCON  FOR AGE OF ANIMAL                                              086
SBC    = STEPHAN-BOLTZMAN CONSTANT                                             239
SIAF   = INCON  FOR FAT GROWTH RATE                           (INTGRL IC)      072
SIAO   = INCON  FOR RATE OF ANIMAL OFFAL GROWTH               (INTGRL IC)      073
SIAS   = INCON  FOR SKELETON GROWTH RATE                      (INTGRL IC)      074
SIAT   = INCON  FOR TISSUE GROWTH RATE                        (INTGRL IC)      075
SQAF   = INCON  FOR FAT WEIGHT                                (INTGRL IC)      062
SQAO   = INCON  FOR OFFAL WEIGHT                              (INTGRL IC)      063
SQAS   = INCON  FOR SKELETON WEIGHT                           (INTGRL IC)      064
SQAT   = INCON  FOR TISSUE WEIGHT                             (INTGRL IC)      065
ST     = PERTURBATION STEP SIZE                                                455
TA     = TEMPORARY STORAGE OF PARAM MULT IN LINEAR SEARCH CALC                 456
TARE   = TIME AT WHICH TARE VALUES ARE LOADED (IN HOURS)                       227
TARTIM = INTERNAL VARIABLE FOR TIME TO LOAD TARE VALUES (SEE TARE)             141
TAVBLD = AVERAGE TEMP  FOR ESTIMATING BLOOD VOLUME            (INTGRL OUT)     030
TAVBX  = DERIVATIVE OF AVG  TEMP  FOR BLOOD VOLUME CALC       (INTGRL IN)      055
TAVE   = CONTROL SIGNAL, AVERAGE BODY TEMPERATURE                              296
TAVEO  = BEGINNING TEMP FOR ESTIMATING BLOOD VOLUME           (INTGRL IC)      080
TB     = TEMPERATURE OF BONE                                  (INTGRL OUT)     026
TBMR   = ERROR SIGNAL FOR BMR BASED ON TEMPERATURE                             457
TBO    = INCON  FOR TEMPERATURE OF BONE                       (INTGRL IC)      076
```

```
TCB     = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TCF     = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TCG     = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TCH     = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TC(6)   = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TCM     = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TCNMN   = MINIMUM TEMPERATURE FOR CONTROL OF THERMAL CONDUCTANCE                 218
TCS     = THERMAL CAPACITY OF COMPONENTS OF EQUIVALENT THERMAL CYLINDER          547
TDELA   = INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                      544
TDELB   = INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                      544
TDELC   = INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                      544
TDELD   = INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                      544
TDELE   = INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                      544
TDELF   = INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                      544
TDEL(6)= INCREMENT TO BE TAKEN ON EACH STEP IN GRID SEARCH                       544
TDNL    = UPPER LIMIT OF TDN                                                     214
TE      = TEMPERATURE OF ENVIRONMENT                                             307
TEA     = TEMPERATURE OF SUN                       (KELVIN DEGREES)              458
TEAFOR = TEMPERTURE OF SUN             TO THE 4TH POWER                          459
TEAMP   = AMPLITUDE OF ENVIRONMENTAL TEMPERATURE VARIATION                       112
TEARTH = TEMP  OF EARTH                                                          309
TEB     = TEMPERATURE OF ENVIRONMENT,              (KELVIN DEGREES)              460
TEBFOR = TEMPERTURE OF ENVIRONMENT     TO THE 4TH POWER                          461
TEC     = TEMPERATURE OF EARTH,                    (KELVIN DEGREES)              462
TECFOR = TEMPERTURE OF EARTH           TO THE 4TH POWER                          463
TEF     = TEMPERATURE OF ENVIRONMENT IN RANKINE DEGREES                          464
TEFX    = EXPONENT  = F(TEF) FOR CALCULATING VAPOR PRESSURE                      455
TELGG   = NATURAL LOGARITHM OF TEF                                               466
TEORD   = ORDINATE OF TEMPERATURE OF ENVIRONMENT                                 111
TEPS    = PHASE SHIFT OF ENVIRONMENTAL TEMPERATURE                               113
TERAMP = AMPLITUDE OF EARTH TEMPERATURE VARIATION                                122
TERORD =  ORDINATE OF TEMPERATURE OF EARTH                                       121
TERPS   = PHASE SHIFT OF EARTH TEMPERATURE                                       123
TERSIN = SINUSOIDAL VARIABLE OF EARTH TEMPERATURE FOR RADIATION                  467
TESIN   = SINUSOIDAL VARIABLE OF ENVIR TEMPERATURE FOR RADIATION                 468
TF      = TEMPERATURE OF FAT                                     (INTGRL OUT)    027
TFEED   = TIME TO FEED MORE GRAIN                                                234
TFO     = INCON  FOR TEMPERATURE OF FAT                          (INTGRL IC)     077
TG      = TEMPERATURE OF GASTROINTESTINAL TRACT                  (INTGRL OUT)    009
TGM     = MAGNITUDE OF GRADIENT VECTOR                                           469
TGO     = INCON FOR TEMPERATURE OF GASTROINTESTINAL TRACT        (INTGRL IC)
TGR(6) = GRADIENT VECTOR IN OPTIM                                                550
TGS     = SQUARED MAGNITUDE OF GRADIENT VECTOR                                   470
TH      = TEMPERATURE OF HAIR                                    (INTGRL OUT)    011
T(6)    = PARAMETER MULTIPLIER VECTOR                                            551
THFOR   = TEMPERTURE OF HAIR            TO THE 4TH POWER                         471
THO     = INCON  FOR TEMPERATURE OF HAIR                         (INTGRL IC)     061
TINVL   = TIME BETWEEN GRAIN FEEDINGS                                            089
TL      = LENGTH ALONG LINE FRCM ORIGIN IN SEARCH ALCNG LINE                     472
TLCK    = MINIMUM STEP SIZE                                                      473
TLD     = STEP SIZE ALONG LINE                                                   474
TLO     = LOCATION OF OPTIMUM POINT ALONG LINE FRCM ORIGIN                       260
TM      = TEMPERATURE OF MEAT                                    (INTGRL OUT)    028
TMAX    = MAXIMUM CONTROL TEMPERATURE AT WHICH EATING IS ALLOWED                 217
```

```
TMIN   = SET POINT TEMPERATURE FOR BMR CONTROL                                 088
TMO    = INCON  FOR TEMPERATURE OF MEAT                        (INTGRL IC)     078
TO(6)  = CURRENT OPTIM PARAM MULT VECTOR IN OPTIM                              549
TOS    = SQUARED MAGNITUDE OF PARAMETER MULTIPLIER                             475
TOT    = TEMPORARY STORAGE OF OPTIMUM PARAMETER MULTIPLIER                     476
TP(6)  = DIRECTION POINTER VECTOR OF LINE IN OPTIM SEARCH                      548
TPL    = MINIMUM PERTURBATION STEP SIZE                                        262
TPM    = MAGNITUDE OF POINTER VECTOR                                           478
TPN    = FLOATING VALUE OF NUMBER OF PARAMETERS                                477
TPS    = SQUARED  MAGNITUDE OF DIRECTION POINTER VECTOR                        479
TPT    = TEMPORARY STORAGE OF POINTER VALUE                                    480
TS     = TEMPERATURE OF SKIN                                   (INTGRL OUT)    010
TSF    = SKIN TEMPERATURE (RANKINE DEGREES)                                    481
TSFX   = CONSTANT FOR VAPOR PRESSURE = F(TSF)                                  482
TSL    = MINIMUM STEP SIZE IN SEARCH                                           263
TSLESS = BOTTOM LIMIT FOR TS BEFORE RECALCULATING WS                           245
TSLGG  = NATURAL LOGARITHM OF SKIN TEMPERATURE                                 483
TSNAMP = AMPLITUDE OF SUN TEMPERATURE VARIATION                                129
TSNORD = ORNINATE OF THE TEMPERATURE OF THE SUN                                128
TSNPS  = PHASE SHIFT OF SUN TEMPERATURE                                        130
TSNSIN = SINUSOIDAL VALUE OF SUN TEMPERATURE FOR RADIATION                     484
TSO    = INCON  FOR TEMPERATURE OF SKIN                        (INTGRL IC)     060
TSPLUS = UPPER TEMPERATURE FOR TS, RECALCULATE WS                              244
TSUN   = TEMP  OF SUN
TX     = TEMPERATURE OF ENVIRONMENTAL RADIATION                                308
TXAMP  = AMPLITUDE OF ENVIRONMENTAL TEMPERATURE FOR RADIATION                  115
TXORD  = ORDINATE FOR ENVIRONMENTAL TEMPERATURE FOR RADIATION                  114
TXPS   = PHASE SHIFT OF ENVIRONMENTAL TEMPERATURE FOR RADIATION                116
TXSIN  = SINUSOIDAL VALUE OF ERV TEMPERATURE FOR RADIATION                     485
URINEF = PERCENT OF FORAGE ENERGY EXCRETED AS URINE                            106
URINEG = PERCENT OF GRAIN ENERGY EXCRETED AS URINE                             096
VACER  = ERROR SIGNAL FOR POWER FROM FAT                                       486
VACERX = CONTROLLED ERROR SIGNAL FOR POWER FROM FAT                            282
VACERZ = STATUS OF CONTROL FOR POWER FROM FAT                  (INTGRL OUT)    031
VACMIN = SETPOINT FOR POWER FROM FAT                                           211
VACO   = INCON  FOR CONTROL FOR POWER FROM FAT                 (INTGRL IC)     081
VBLD   = ENERGY DENSITY OF BLOOD ACETATE                                       301
VEN( ) = CONSTANT TO CALC EMPIRICAL VENTILATION RATE                           507
VFATLG = LAG OF POWER FROM FAT                                                 212
VFATX  = DERIVATIVE OF CONTROL FOR POWER FROM FAT              (INTGRL IN)     056
VPR    = POTENTIAL FOR PRODUCT                                                 487
VRATIO = VENTILATION RATE TO BASIC VENTILATION RATE                            318
VTBMLG = LAG OF BMR CONTROLLER                                                 195
VTBMRX = CONTOLLED ERROR SIGNAL FOR BMR STATUS                 (INTGRL IN)     054
VTBMRZ = INTEGRATED SIGNAL FOR BMR CONTROL                     (INTGRL OUT)    029
VWCON  = CONVERSION OF WATER VAPOR TO HEAT EQUIVALENT                          240
VWCONA = A CONVERSION FACTOR FOR MOISTURE LOSS PER AREA                        488
WE     = HUMIDITY RATIO OF ENVIRONMENT                                         489
WS     = HUMIDITY RATIO FOR MOISTURE/AIR AT SKIN TEMPERATURE,SATURATION        490
XA     = INITAL VALUES FOR PARAM TO BE OPTIMIZED                               522
XB     = INITAL VALUES FOR PARAM TO BE OPTIMIZED                               522
XC     = INITAL VALUES FOR PARAM TO BE OPTIMIZED                               522
XD     = INITAL VALUES FOR PARAM TO BE OPTIMIZED                               522
XE     = INITAL VALUES FOR PARAM TO BE OPTIMIZED                               522
```

```
XF      = INITAL VALUES FOR PARAM TO BE OPTIMIZED                        522
XX(6)   = INITAL VALUES FOR PARAM TO BE OPTIMIZED                        522
ZZ0039 = IAO                                              (INTGRL IN)   038
ZZ0037 = IAS                                              (INTGRL IN)   039
ZZ0038 = IAT                                              (INTGRL IN)   040
```

VITA

Myron David Paine

Candidate for the Degree of

Doctor of Philosophy

Thesis: MATHEMATICAL MODELING OF ENERGY METABOLISM IN BEEF ANIMALS

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Ree Heights, South Dakota, June 27, 1934, the son of David and Vera Paine.

Education: Graduated from Hazel High School, Hazel, South Dakota, in 1952; graduated from South Dakota State University, Brookings, South Dakota, with a Bachelor of Science degree in Agricultural Engineering in 1956; received the Master of Science degree in Agricultural Engineering from Illinois University, Champagne, Urbana, in 1957; completed the requirements for Doctor of Philosophy degree from Oklahoma State University, Stillwater, Oklahoma, in July, 1971, while studying as a National Science Foundation Faculty Fellow.

Professional Experience: Army Engineer Corps, 2nd Lieutenant, 1957; Instructor and then Assistant Professor in Agricultural Engineering, South Dakota State University, 1957-1963; Team Leader for International Voluntary Service, Laos, 1963-1965; Field Supervisor, Air America, Laos, 1965-1966; Assistant Professor in Agricultural Engineering Extension, Oklahoma State University, 1966-1970.

Professional and Honorary Organizations: Member of the American Society of Agricultural Engineers, Registered Professional Engineer in Oklahoma, Phi Kappa Phi, Sigma Tau, Gamma Sigma Delta, Who's Who Among Students in American Universities and Colleges.